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GAS TURBINE REGENERATORS: A METHOD FOR SELECTING THE OPTIMUM PLATE-FINNED SURFACE PAIR FOR MINIMUM CORE VOLUME

by

JOSEPH FRANCIS CAMPBELL, JR.

B. S. Mech. Eng., University of Pennsylvania
(1980)

SUBMITTED TO THE DEPARTMENT OF
OCEAN ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
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at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June, 1989

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A METHOD FOR SELECTING THE OPTIMUM PLATE-FINNED SURFACE PAIR FOR MINIMUM CORE VOLUME

by

JOSEPH FRANCIS CAMPBELL, JR.
Lieutenant, United States Navy

Submitted to the Department of Ocean Engineering on May 12, 1989 in partial fulfillment of the requirements for the degrees of Naval Engineer and Master of Science in Mechanical Engineering.

ABSTRACT

Based on a power law curve fit for the Soland et al. [2] modification of the Kays-London [1] way of presenting heat exchanger performance, a closed-form solution for sizing counterflow regenerators is derived. After applying this method to many Kays-London plate-finned surfaces, the optimum surface pair for minimum heat exchanger core volume is found to be 1/9-24.12 and 1/10-19.35. In general, the minimum core volume will be obtained by following a three step process: 1) select a surface for the high pressure side having the minimum plate spacing commensurate with cleaning constraints; 2) list all other available surfaces with plate spacings nearly equal to the selected high pressure side plate spacing (i.e. $b_2/b_1 \cong 1.0$); 3) select from this list the surface with the minimum hydraulic diameter for use on the low pressure side.

THESIS SUPERVISOR: Professor Warren M. Rohsenow
TITLE: Professor of Mechanical Engineering, Emeritus

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I would also like to acknowledge those special people that have shaped my life:

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NOMENCLATURE

Symbol	Definition	Units
a	thickness of plate separating heat exchanger sides	ft
A_b	heat transfer area of base surface which includes the effect of fins; equals length times heated perimeter	ft^2
A_c	minimum free flow area	ft^2
A_F	flow area ignoring any fins	ft^2
A_T	total heat transfer area	ft^2
b	plate spacing	ft
c_p	specific heat	Btu/lb_m-°F
D_n	nominal diameter; defined by (1b)	ft
f	friction factor based on total area (A_T); defined by (4a)	
f_n	friction factor based on base area (A_b); defined by (4b)	
g_o	conversion factor (= 32.174 lb_m-ft/lb_f-sec^2)	
G_c	mass flux based on minimum free flow area; defined by (2a)	lb_m/hr-ft^2
G_n	mass flux based on free flow area (A_F); defined by (2b)	lb_m/hr-ft^2
h	heat transfer coefficient based on total area (A_T); defined by (5a)	Btu/hr-ft^2-°F
h_n	heat transfer coefficient based on base area (A_b); defined by (5b)	Btu/hr-ft^2-°F
j	Colburn j-factor based on total area (A_T); defined by (6a)	
j_n	Colburn j-factor based on base area (A_b); defined by (6b)	
k	thermal conductivity of heat exchanger metal	Btu/hr-ft-°F
K_f	y-axis intercept of "new best-fit" line with slope = -s; defined by (16b)	
K_j	y-axis intercept of "new best-fit" line with slope = -s; defined by (16a)	
L_f	fin length from root to center (=b/2)	ft
m	component of fin efficiency (η_f); defined by (9)	
P	component of core volume formula derived according to pressure drop considerations; defined by (26)	$ft^{(3-2S)}$
q	heat transfer rate	Btu/hr
q/A	heat flux	Btu/hr-ft^2

Q	component of core volume formula derived according to heat transfer considerations; defined by (34)	$ft^{(2S+1)}$
r	correlation coefficient	
r_h	hydraulic radius; defined by (1a)	ft
R	gas constant	ft-lb/lb-°F
s	average slope of all best-fit lines through j_n and f_n vs. Re_n data points	
T	temperature	°F
U	overall heat transfer coefficient	$Btu/hr\text{-}ft^2\text{-}°F$
V	volume	ft^3
X	heat exchanger width	ft
(XY)	heat exchanger frontal area	ft^2
Y	heat exchanger height	ft
Z	heat exchanger length	ft

DIMENSIONLESS GROUPS

Pr	Prandtl number
Re	Reynolds number based on minimum free flow area (A_c); defined by (3a)
Re_n	Reynolds number based on free flow area (A_F); defined by (3b)

SUBSCRIPTS

n	denotes a parameter modified according to Soland's method [2]
1,2	indicates different sides of heat exchanger

MISCELLANEOUS

α	ratio of total area on one side of the heat exchanger to total volume of the heat exchanger; defined by (17)	ft^{-1}
β	ratio of total heat transfer area on one side to the volume on that side	ft^{-1}
δ	fin thickness	ft
δT	temperature difference; as shown in Figure 5	°F
ΔT	temperature difference; as shown in Figure 5	°F
Δp	friction pressure drop	lb_f/ft^2
ε	heat exchanger effectiveness	
η_f	fin efficiency; defined by (8)	
η_o	total surface temperature effectiveness; defined by (7)	
σ	ratio of free flow area to frontal area; defined by (19)	
μ	viscosity	$lb_m/hr\text{-}ft$
ρ	density	lb_m/ft^3
ω	mass flow rate	lb_m/hr

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1 INTRODUCTION

When designing gas turbine regenerators for a given application, often the goal is to minimize volume. In the past, methods for sizing counterflow plate-finned regenerators were iterative and methods for selecting the optimal (minimum core volume) surface pair were complex and iterative in nature [1]. In this paper, an approximate closed-form solution for the sizing problem is derived and a set of criteria for choosing the optimal surface pair is presented. After the surfaces on each side have been selected, the final sizing and design must be re-calculated using the method of Kays-London [1].

2 BACKGROUND

Kays and London [1], hereafter denoted as K-L, present data for many plate-finned surfaces in terms of heat transfer coefficients, h, and friction factors, f, referred to the exposed area, A_T, as a function of Reynolds number, based on the minimum free-flow area, A_c. Soland et al [2] present a method which converts these h and f magnitudes to the base plate area, A_b. Table 1 shows Soland's definitions of the various quantities compared with the definitions used by K-L.

Table 1. Definitions

Quantity	Kays and London [1]	Soland [2]
hydraulic diameter or radius	$r_h \equiv \frac{A_c Z}{A_T}$ (1a)	$D_n \equiv \frac{4A_F Z}{A_b} = \frac{4V}{A_b}$ (1b)
mass flux	$G_c \equiv \frac{\omega}{A_c}$ (2a)	$G_n \equiv \frac{\omega}{A_F}$ (2b)
Reynolds number	$Re \equiv \frac{4G_c r_h}{\mu}$ (3a)	$Re_n \equiv \frac{G_n D_n}{\mu}$ (3b)
friction factor	$f \equiv \frac{(\Delta p) r_h (2\rho g_o)}{Z G_c^2}$ (4a)	$f_n \equiv \frac{(\Delta p) D_n (2\rho g_o)}{4Z G_n^2}$ (4b)
heat transfer coefficient	$h \equiv \frac{q/\eta_o A_T}{\Delta T}$ (5a)	$h_n \equiv \frac{q/A_b}{\Delta T}$ (5b)
Colburn j-factor	$j \equiv \frac{h}{G_c c_p}(Pr)^{2/3}$ (6a)	$j_n \equiv \frac{h_n}{G_n c_p}(Pr)^{2/3}$ (6b)

The efficiencies are defined by (7), (8), and (9).

$$\eta_o \equiv 1 - \frac{(XY)}{A_T}(1-\eta_f) \tag{7}$$

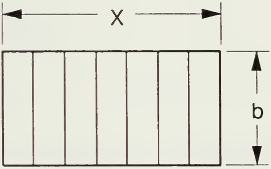
$$\eta_f \equiv \frac{\tanh(mL_f)}{(mL_f)} \tag{8}$$

$$m \equiv \sqrt{\frac{2h}{\delta k}} \tag{9}$$

Below is a pertinent excerpt from Soland's paper:

> The effect of the fins is included in the new h_n and f_n based on A_b. Further, the new Reynolds number, Re_n, is based on the open flow, A_F, as though the fins were not present. This requires that the metal conductivity of the fins be specified in incorporating the effect of the fins into h_n.

Note from Figure 1, $D_n = 2b$ for a rectangular parallel plate passage.



$A_F = Xb$

$A_b = 2XZ$

$V = XZb$

$D_n = 4\frac{V}{A_b} = 4\frac{XZb}{2XZ} = 2b$

$G_n = \frac{\omega}{A_F} = \frac{\omega}{Xb}$

Figure 1. Sample Calculation of Nominal Diameter and Mass Flux for Rectangular Flow Passage

To convert the data of K-L to Soland's basis, the following ratios can be obtained from the definitions, (1) through (9), and Figure 1.

$$\frac{A_b}{A_T} = \frac{2XZ}{\beta V} = \frac{2}{\beta b} \tag{10}$$

where

$$\beta \equiv \frac{A_T}{V} \qquad \left(\text{and} \quad \beta_n \equiv \frac{A_b}{V} = \frac{2}{b} \right) \tag{11}$$

The other ratios are:

$$\frac{A_F}{A_c} = \frac{X\,Z\,b}{A_T\,r_h} = \frac{1}{\beta\,r_h} \tag{12}$$

$$\frac{G_n}{G_c} = \frac{A_c}{A_F} = \beta\,r_h \tag{13}$$

$$\frac{Re_n}{Re} = \frac{D_n\,G_n}{4\,r_h\,G_c} = \frac{\beta\,b}{2} \tag{14}$$

$$\frac{f_n}{f} = \frac{A_F\,A_T\,G_c^2}{A_c\,A_b\,G_n^2} = \frac{b}{2\,\beta^2\,r_h^3} \tag{15}$$

$$\frac{j_n}{j} = \frac{h_n}{h}\frac{G_c}{G_n} = \frac{\eta_o\,b}{2\,r_h} \tag{16}$$

These ratios are used to convert K-L data to the modified j_n and f_n vs. Re_n curves obtained by Soland. Two assumptions are necessary to solve for the proper fin efficiency, η_f, required for the conversion. The heat exchanger in this study is constructed from steel ($k \cong$ 12 Btu/ft-hr-°F) and the gas properties are evaluated for air at 750°F. Figure 2 shows the two pairs of curves on both bases for a typical K-L surface, namely their 3/16-11.1 plate-finned surface, Figure 10.44 of reference [1].

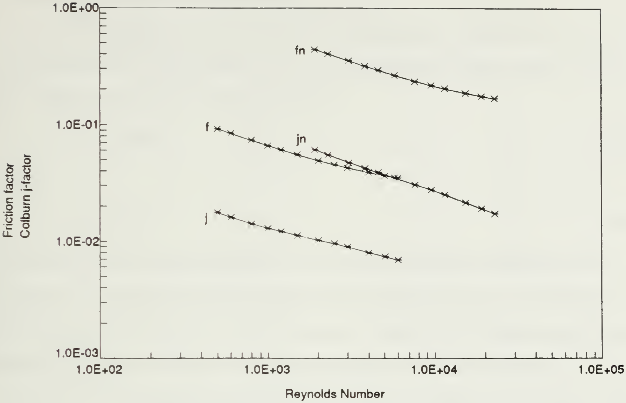


Figure 2. j and f vs. Re; j_n and f_n vs. Re_n for Surface 3/16-11.1

3 DERIVATION OF SIZING METHOD

Several preliminary steps are necessary before deriving the sizing method. First is the key approximation of fitting straight lines through the modified K-L data points, j_n and f_n vs. Re_n. These lines have the functional relationships:

$$j_n = K_j Re_n^{-s} \tag{17a}$$

and

$$f_n = K_f Re_n^{-s} \tag{17b}$$

where K_j and K_f are y-axis intercepts and -s is the slope of the line on a log-log plot. The values for s, K_j, and K_f are determined using a linear regression routine. A "best-fit" line is found for each surface's j_n and f_n vs. Re_n data points. Tables 2a and 2b list the slopes of these best-fit lines with the associated correlation coefficient, r (defined in reference [3]), for each of the 26 K-L surfaces examined in this study. Generally, the j_n and f_n vs. Re_n data are well represented by straight lines as evidenced by the fact that all correlation coefficients are greater than 0.93. Figures 3a and 3b are histograms of the slopes for j_n and f_n vs. Re_n for all surfaces considered by this paper. By averaging the slopes from Tables 2a and 2b, the value to be used for s in (17a) and (17b) is found to be 0.46.

Table 2a. j_n vs. Re_n						
Surface name from K-L [1]	Name used in Fig. 6	Plate Spacing, b	Nominal Plate Spacing	slope	r	K_j
1/10-19.74	S27	0.0042	0.006	-0.440	0.995	0.656
1/10-19.35	S29	0.0063		-0.484	0.999	1.069
1/9-24.12	S28	0.0063		-0.434	0.993	1.312
3/8(b)-11.1	L19	0.0208	0.021	-0.486	0.999	1.746
3/4-11.1	L21	0.0208		-0.484	0.999	1.396
3/8-11.1	L18	0.0208		-0.506	0.999	1.773
3/16-11.1	L15	0.0208		-0.497	0.999	1.872
11.1	P04	0.0208		-0.395	0.983	0.932
1/2-11.1	L20	0.0208		-0.473	0.997	1.514
3/4(b)-11.1	L22	0.0208		-0.459	0.999	1.380
1/8-16.12T	S31	0.0261	0.028	-0.607	0.998	4.440
14.77	P06	0.0275		-0.503	0.996	1.615
30.33T	P10	0.0287		-0.790	0.999	4.314
1/6-12.18D	S30	0.0294		-0.641	0.999	2.656
6.2	P02	0.0337	0.034	-0.306	0.938	0.686
17.8-3/8W	W27	0.0345		-0.612	0.999	4.046
11.44-3/8W	W26	0.0345		-0.549	0.999	3.014
1/8-15.2	S25	0.0346		-0.489	0.999	3.575
15.08	P07	0.0348		-0.621	0.986	1.447
5.3	P01	0.0392	0.040	-0.403	0.996	0.987
11.11(a)	P05	0.0400		-0.396	0.936	2.046
3/32-12.22	S24	0.0404		-0.584	0.999	2.899
3.97	P14	0.0625	0.064	-0.331	0.989	1.274
2.0	P12	0.0625		-0.313	0.997	0.790
3.01	P13	0.0625		-0.339	0.987	1.007
9.03	P03	0.0686		-0.537	0.987	1.625

Note: The intercept K_j is determined for the average slope equal to -0.46.

Table 2b. f_n vs. Re_n

Surface name from K-L [1]	Name used in Fig. 6	Plate Spacing, b	Nominal Plate Spacing	slope	r	K_f
1/10-19.74	S27	0.0042	0.006	-0.457	0.977	3.919
1/10-19.35	S29	0.0063		-0.522	0.992	5.265
1/9-24.12	S28	0.0063		-0.493	0.988	8.737
3/8(b)-11.1	L19	0.0208	0.021	-0.376	0.980	11.561
3/4-11.1	L21	0.0208		-0.454	0.982	8.060
3/8-11.1	L18	0.0208		-0.388	0.982	11.806
3/16-11.1	L15	0.0208		-0.395	0.995	14.766
11.1	P04	0.0208		-0.441	0.960	4.141
1/2-11.1	L20	0.0208		-0.375	0.971	9.436
3/4(b)-11.1	L22	0.0208		-0.429	0.982	8.068
1/8-16.12T	S31	0.0261	0.028	-0.378	0.965	52.575
14.77	P06	0.0275		-0.493	0.972	10.369
30.33T	P10	0.0287		-0.807	0.991	29.905
1/6-12.18D	S30	0.0294		-0.498	0.985	18.694
6.2	P02	0.0337	0.034	-0.371	0.943	3.092
17.8-3/8W	W27	0.0345		-0.435	0.999	45.642
11.44-3/8W	W26	0.0345		-0.391	1.000	34.107
1/8-15.2	S25	0.0346		-0.335	0.969	47.617
15.08	P07	0.0348		-0.640	0.969	7.032
5.3	P01	0.0392	0.040	-0.458	0.972	3.226
11.11(a)	P05	0.0400		-0.516	0.959	8.833
3/32-12.22	S24	0.0404		-0.385	0.980	41.038
3.97	P14	0.0625	0.064	-0.260	0.969	5.607
2.0	P12	0.0625		-0.212	0.976	2.648
3.01	P13	0.0625		-0.264	0.968	4.448
9.03	P03	0.0686		-0.418	0.946	12.057

Note: The intercept K_f is determined for the average slope equal to -0.46.

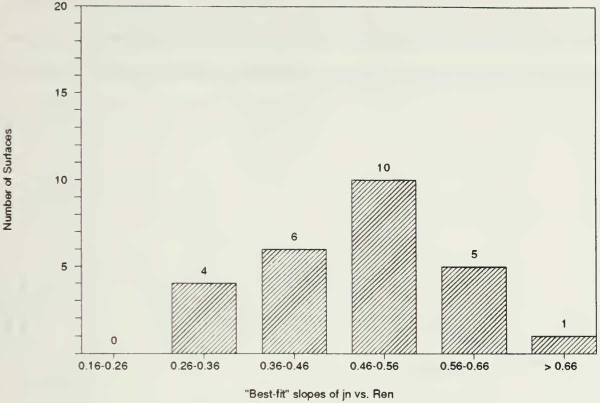


Figure 3a. Histogram of slopes for j_n vs. Re_n

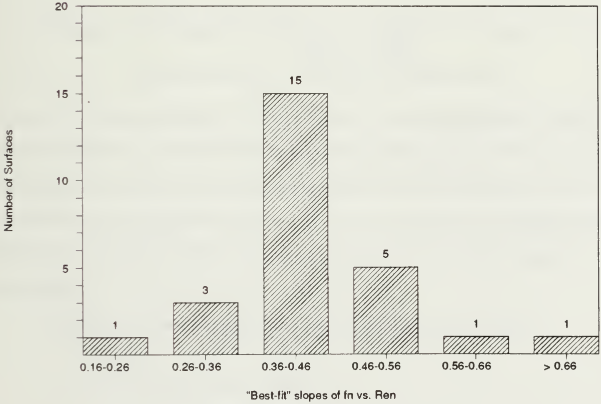


Figure 3b. Histogram of slopes for f_n vs. Re_n

With s thus determined, the j_n and f_n vs. Re_n data for each surface is revisited. This time, "new best-fit" lines are determined but the slopes of the lines are fixed at s equal to 0.46 for all surfaces. A plot of this kind is included for the typical surface 3/16-11.1 as Figure 4.

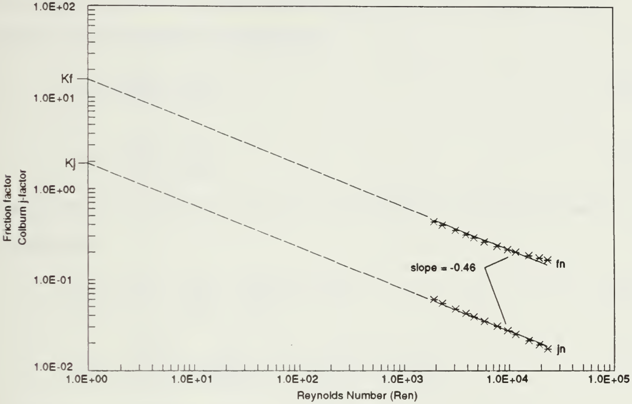


Figure 4. Surface 3/16-11.1 "New Best-Fit" Line (slope = -0.46)

The y-axis intercepts, K_j and K_f, for surface 3/16-11.1 are shown graphically on Figure 4. The intercepts of the new best-fit lines for the other surfaces are listed in Tables 2a and 2b. For the surface 3/16-11.1, the average error between the new best-fit line (slope equal to -0.46) and the f_n data points is 2% and for j_n is 1%. For a discussion of the method used to calculate the average error and for plots similar to Figure 4 for the other surfaces, see Appendix A.

Next, define two heat exchanger core geometrical parameters, α_n and σ_n.

$$\alpha_{n1} \equiv \frac{A_{b1}}{V_T} = \frac{2}{b_1 + b_2 + 2a} \cong \frac{2}{b_1 + b_2} \tag{18a}$$

$$\alpha_{n2} \equiv \frac{A_{b2}}{V_T} \equiv \frac{2}{b_1 + b_2} = \alpha_1 \tag{18b}$$

Note that in (18a) and (18b) the heat transfer resistance of the plate (thickness = a) separating the two sides of the heat exchanger is considered negligible and therefore the "2a" term is dropped. The other geometrical parameter is:

$$\sigma_{n1} \equiv \frac{A_{F1}}{(XY)} = \frac{b_1}{b_1 + b_2} \tag{19a}$$

$$\sigma_{n2} \equiv \frac{A_{F2}}{(XY)} = \frac{b_2}{b_1 + b_2} \tag{19b}$$

The mass flux, G_n and Reynolds number, Re_n can be written in terms of these geometrical parameters as:

$$G_{n1} = \frac{\omega_1}{A_{F1}} = \frac{\omega_1}{\sigma_{n1}(XY)} = \frac{\omega_1}{(XY)}(1 + b_2/b_1) \tag{20}$$

$$Re_{n1} = \frac{G_{n1} D_{n1}}{\mu_1} = \frac{\omega_1}{\sigma_{n1}(XY)} \frac{2b_1}{\mu_1} = \frac{\omega_1}{(XY)} \frac{2b_1}{\mu_1}(1 + b_2/b_1) \tag{21}$$

with similar results for G_{n2} and Re_{n2}.

The remaining preliminary step is to specify the operating conditions for which the regenerator will be sized. For this study, side one of the regenerator is the cold, high pressure side. The mass flow rates are assumed given and equal on both sides:

$\omega_1 = \omega_2 = 108.7$ lb$_m$/sec

The other given conditions are:

inlet pressures: $p_1 = 268.14$ psi; $p_2 = 16.04$ psi

allowable combined pressure drop: $\Sigma(\Delta p/p) = 0.08$

inlet temperatures: $T_{1in} = 1012.6$°R; $T_{2in} = 1434.2$°R

effectiveness: $\varepsilon_1 = \varepsilon_2 = 0.90$

Note that with the inlet temperatures and the effectiveness specified, it is a simple task to compute the outlet temperatures and the average temperatures on both sides, T_1 and T_2.

Having completed the above preliminary steps, it is now possible to derive the approximate closed-form formula for sizing a counterflow regenerator. The derivation consists of three steps. First, the heat exchanger core size (X,Y, and Z) is found as a function of the allowable pressure drop. Step two finds the core size based on heat transfer considerations. In step three, the equations resulting from steps one and two are solved simultaneously to yield the formula for core volume.

STEP 1. From (4b), the pressure drop equation can be written as:

$$\frac{\Delta p_1}{p_1} = \frac{4 f_{n1} Z_1 G_{n1}^2}{p_1 (2 \rho_1 g_o) D_{n1}} \tag{22}$$

Substitute for f_n using (17b), use $Z_1 = Z_2 = Z$ for counterflow arrangement and substitute for $2b_1 = D_n$ from Figure 1:

$$\frac{\Delta p_1}{p_1} = \frac{4 K_{f1} Re_{n1}^{-S}}{\rho_1 p_1} \frac{Z}{2b_1} \frac{G_{n1}^2}{2 g_o} \tag{23}$$

Substitute for G_n from (20) and Re_n from (21) and rearrange:

$$\frac{\Delta p_1}{p_1} = \frac{2 K_{f1} Z \mu_1^S}{p_1 \rho_1 g_o (2b_1)^{S+1}} \left(\frac{\omega}{(XY)} (1 + b_2/b_1) \right)^{2-S} \tag{24a}$$

Similarly,

$$\frac{\Delta p_2}{p_2} = \frac{2 K_{f2} Z \mu_2^S}{p_2 \rho_2 g_o (2b_2)^{S+1}} \left(\frac{\omega}{(XY)} (1 + b_1/b_2) \right)^{2-S} \tag{24b}$$

Combining (24a) and (24b) and letting $\mu_1 = \mu_2 = \mu$

$$\Sigma\frac{\Delta p}{p}=\frac{\Delta p_1}{p_1}+\frac{\Delta p_2}{p_2}$$

$$=\frac{2Z\mu^S}{g_o}\left(\frac{\omega}{(XY)}\right)^{2-S}\left(\frac{K_{f1}(1+b_2/b_1)^{2-S}}{p_1\rho_1(2b_1)^{S+1}}+\frac{K_{f2}(1+b_1/b_2)^{2-S}}{p_2\rho_2(2b_2)^{S+1}}\right) \tag{25}$$

Define the heat exchanger size in terms of pressure drop as P:

$$\mathrm{P}\equiv\frac{(XY)^{2-S}}{Z} \tag{26}$$

Substituting ρ = RT/p from the ideal gas relationship, then from (25) and (26):

$$\mathrm{P}=\frac{2RT_1\mu^S\omega^{2-S}}{\Sigma\left(\frac{\Delta p}{p}\right)g_o p_1^2}\frac{K_{f1}}{(2b_1)^{S+1}}(1+b_2/b_1)^{2-S}\left(1+\frac{K_{f2}}{K_{f1}}\left(\frac{p_1}{p_2}\right)^2\frac{T_2}{T_1}\left(\frac{b_1}{b_2}\right)^3\right) \tag{27}$$

STEP 2. The heat transfer rate equation from [4] is:

$$q=U\,A_b\,(\Delta T) \tag{28}$$

where

$$\frac{1}{U\,A_b}=\left(\frac{1}{h_n A_b}\right)_1+\left(\frac{1}{h_n A_b}\right)_2 \tag{29}$$

From (6b):

$$h_{n1}=j_{n1}\frac{c_{p1}G_{n1}}{(Pr_1)^{2/3}} \tag{30}$$

Substitute for j_{n1} using (17a):

$$h_{n1}=K_{j1}\frac{c_{p1}}{(Pr_1)^{2/3}}Re_{n1}^{-S}G_{n1} \tag{31}$$

Substitute for G_n from (20), Re_n from (21), let $Pr_1 = Pr_2 = Pr$, $c_{p1} = c_{p2} = c_p$ and rearrange:

$$\frac{1}{h_{n1}}=\frac{Pr^{2/3}}{c_p}\left(\frac{(XY)}{\omega}\right)^{1-S}\frac{1}{\mu^S}\left(\frac{1}{K_{j1}}\left(\frac{b_1}{b_1+b_2}\right)^{1-S}(2b_1)^S\right) \tag{32a}$$

Similarly,

$$\frac{1}{h_{n2}}=\frac{Pr^{2/3}}{c_p}\left(\frac{(XY)}{\omega}\right)^{1-S}\frac{1}{\mu^S}\left(\frac{1}{K_{j2}}\left(\frac{b_2}{b_1+b_2}\right)^{1-S}(2b_2)^S\right) \tag{32b}$$

Combining (32a) and (32b) with (28) and (29) and using:

$$A_b=\alpha_n(XYZ)=\frac{2(XYZ)}{(b_1+b_2)}$$

from (18), then:

$$\frac{\Delta T}{q}=\frac{(b_1+b_2)Pr^{2/3}}{2(XY)^S Z c_p \omega^{1-S}\mu^S}\left(\frac{1}{K_{j1}}\left(\frac{b_1}{b_1+b_2}\right)^{1-S}(2b_1)^S+\right.$$

$$\left.\frac{1}{K_{j2}}\left(\frac{b_2}{b_1+b_2}\right)^{1-S}(2b_2)^S\right) \tag{33}$$

Define the heat exchanger size in terms of heat transfer as Q:

$$\mathrm{Q}\equiv(XY)^S Z \tag{34}$$

Then substituting (33) into (34) and rearranging:

$$\mathrm{Q}=\frac{(b_1+b_2)q\,Pr^{2/3}}{2\,(\Delta T)\,c_p\,\omega^{1-S}\mu^S}\left(\left(\frac{b_1}{b_1+b_2}\right)^{1-S}\frac{(2b_1)^S}{K_{j1}}+\left(\frac{b_2}{b_1+b_2}\right)^{1-S}\frac{(2b_2)^S}{K_{j2}}\right) \tag{35}$$

Make the substitution $q=\omega c_p \delta T$ (where the relationship between ΔT and δT is shown in Figure 5) and rearrange:

$$\mathrm{Q}=\left(\frac{\delta T}{\Delta T}\frac{\omega^S Pr^{2/3}}{\mu^S}\right)\left(\frac{b_1^{S+1}}{2^{1-S}K_{j1}}\right)\left(1+\frac{b_2}{b_1}\right)^S\left(1+\frac{K_{j1}b_2}{K_{j2}b_1}\right) \tag{36}$$

STEP 3. The definitions for P (26) and Q (34) provide two equations for the two unknowns, (XY) and Z. Solving these simultaneously, the closed-form solution for the heat exchanger core volume is:

$$\mathrm{V}=\mathrm{P}^{\frac{1-S}{2}}\mathrm{Q}^{\frac{3-S}{2}} \tag{37}$$

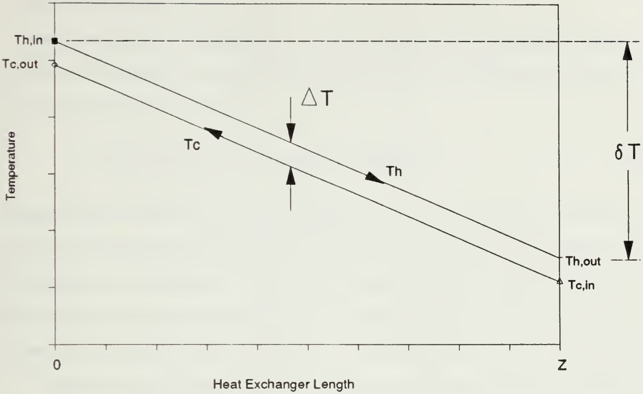


Figure 5. Definition of ΔT and δT for a counterflow heat exchanger with $(\omega c_p)_1 = (\omega c_p)_2$

4 ANALYSIS AND RESULTS

Examination of (27), (36) and (37) reveals that for a given set of operating conditions (such as those previously described), if the surface on side one is specified then the volume of the heat exchanger is such that:

$$V = f\left[\frac{b_2}{b_1}, \frac{K_{f2}}{K_{f1}}, \left(\frac{K_{j2}}{K_{j1}}\right)^{-1}, \text{operating conditions}\right] \tag{38}$$

Using the design conditions previously specified and the typical surface 3/16-11.1 on side one, heat exchanger volumes are calculated for this surface paired with every other surface. The results are shown in Table 3. Appendix B includes tables similar to Table 3 for all the other surfaces on side one. Of the 600 surface pairs examined, the combination of 1/9-24.12 on side one with 1/10-19.35 on side two results in the minimum heat exchanger core volume.

As shown in Tables 2a and 2b, the 26 K-L surfaces included in this study are divided into six nominal plate-spacing groups. The volumes from Table 3 are grouped by nominal b_2/b_1 ratio and then each group is graphed as a function of K_{f2}/K_{f1}. Lines of constant K_{j2}/K_{j1} are also plotted. For the typical surface 3/16-11.1, plots for five nominal b_2/b_1 ratios are included as Figures 6a through 6e. From these figures it is apparent that volume is minimized when K_{f2}/K_{f1} is minimized, K_{j2}/K_{j1} is maximized, and b_2/b_1 is approximately one. A pair of "ideally designed" surfaces would meet these criteria and result in the minimum core volume.

As a practical matter, surfaces similar to these studied here are not designed to be paired so as to result in optimal ratios of K_{f2}/K_{f1} and K_{j2}/K_{j1}. Rather, when designing a surface the geometrical parameters such as plate spacing, fins/inch, (hydraulic diameter), and fin thickness are varied. Then the heat transfer and friction characteristics of the surface are experimentally determined. For this reason, the behavior of real surface pairs must be studied.

From the data in Table 3 (and the data in Appendix B for other side one surfaces) a relationship can be developed between heat exchanger volume, hydraulic diameter, and plate spacing ratio. Figure 7a is a plot of heat exchanger volume versus hydraulic diameter when the typical surface 3/16-11.1 is on side one. Six nominal plate spacing ratios are plotted. From this figure, it is seen that increasing hydraulic diameter results in larger volume.

The same volumes from Table 3 are plotted in Figure 7b but this time as a function of plate spacing ratio. The relationship between increasing hydraulic diameter and larger volume is clearly shown in this graph. An additional result that can be seen from this figure is that for comparable hydraulic diameters and plate spacing ratios, interrupted fin surfaces generally result in smaller volumes than continuous fin surfaces. Also, although the curves of volume versus plate spacing ratio are relatively flat for any range of hydraulic diameter, Figure 7b generally confirms the result from Figure 6 that minimum volume occurs when the plate spacing ratio is near one. Figures 8a, 8b and 9a, 9b show results similar to Figure 7 for other surfaces on side one. Figure 8 has surface 1/9-24.12 on side one. This is the side one surface which results in the minimum heat exchanger volume. Figure 9 has surface 17.8-3/8W on side one. This is the surface that Soland determined to be "best" [2].

Table 3. Side One: 3/16-11.1					
Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	436.7	0.2	0.35	0.27
1/10-19.35	0.00460	356.4	0.3	0.57	0.36
1/9-24.12	0.00397	375.8	0.3	0.70	0.59
3/8(b)-11.1	0.01012	377.9	1.0	0.93	0.78
3/4-11.1	0.01012	400.5	1.0	0.75	0.55
3/8-11.1	0.01012	376.2	1.0	0.95	0.80
3/16-11.1	0.01012	385.8	1.0	1.00	1.00
11.1	0.01012	460.7	1.0	0.50	0.28
1/2-11.1	0.01012	394.1	1.0	0.81	0.64
3/4(b)-11.1	0.01012	404.0	1.0	0.74	0.55
1/8-16.12T	0.00514	362.4	1.3	2.37	3.56
14.77	0.00848	439.1	1.3	0.86	0.70
30.33T	0.00401	322.1	1.4	2.30	2.03
1/6-12.18D	0.00885	374.4	1.4	1.42	1.27
6.2	0.01820	809.1	1.6	0.37	0.21
17.8-3/8W	0.00696	394.7	1.7	2.16	3.09
11.44-3/8W	0.0106	435.3	1.7	1.61	2.31
1/8-15.2	0.00868	429.0	1.7	1.91	3.22
15.08	0.00876	502.2	1.7	0.77	0.48
5.3	0.02016	648.5	1.9	0.53	0.22
11.11(a)	0.01153	439.2	1.9	1.09	0.60
3/32-12.22	0.01120	509.3	1.9	1.55	2.78
3.97	0.02820	916.8	3.0	0.68	0.38
2.0	0.04740	1321.9	3.0	0.42	0.18
3.01	0.03546	1119.3	3.0	0.54	0.30
9.03	0.01522	942.0	3.3	0.87	0.82

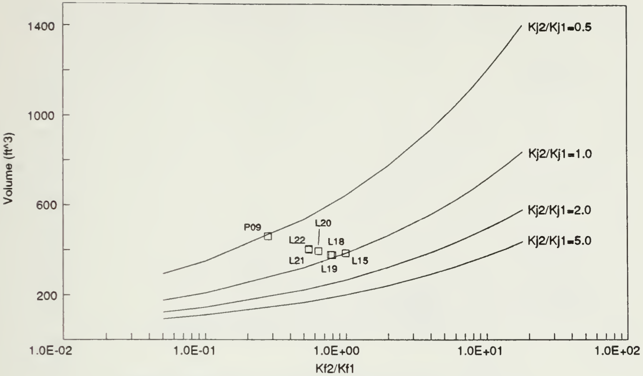


Figure 6a. Volume vs. K_{f2}/K_{f1}. Side One Surface 3/16-11.1: $b_2/b_1 = 1.0$

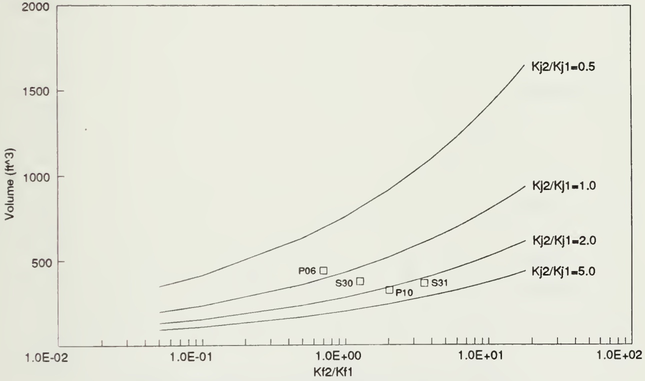


Figure 6b. Volume vs. K_{f2}/K_{f1}. Side One Surface 3/16-11.1: $b_2/b_1 = 1.3$

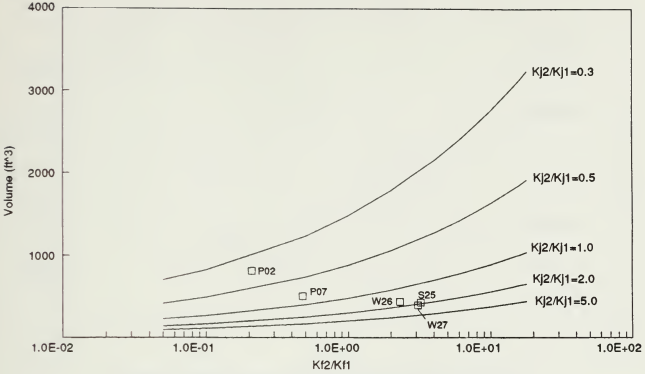


Figure 6c. Volume vs. K_{f2}/K_{f1}. Side One Surface 3/16-11.1: $b_2/b_1 = 1.6$

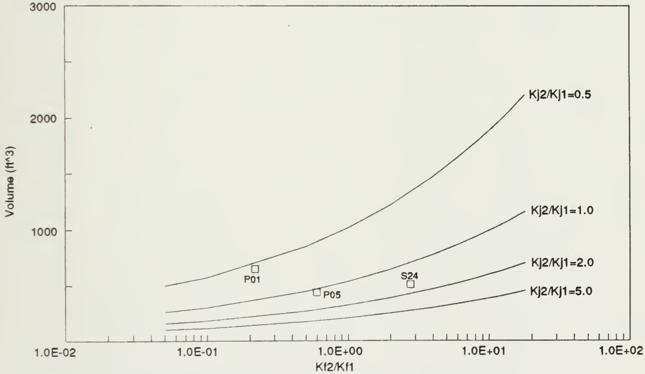


Figure 6d. Volume vs. K_{f2}/K_{f1}. Side One Surface 3/16-11.1: $b_2/b_1 = 1.9$

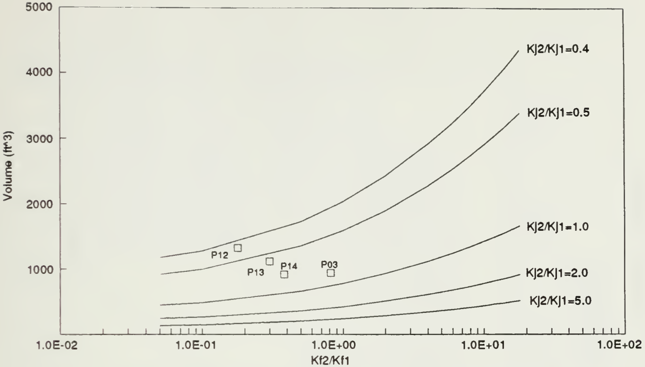


Figure 6e. Volume vs. K_{f2}/K_{f1}. Side One Surface 3/16-11.1: $b_2/b_1 = 3.0$

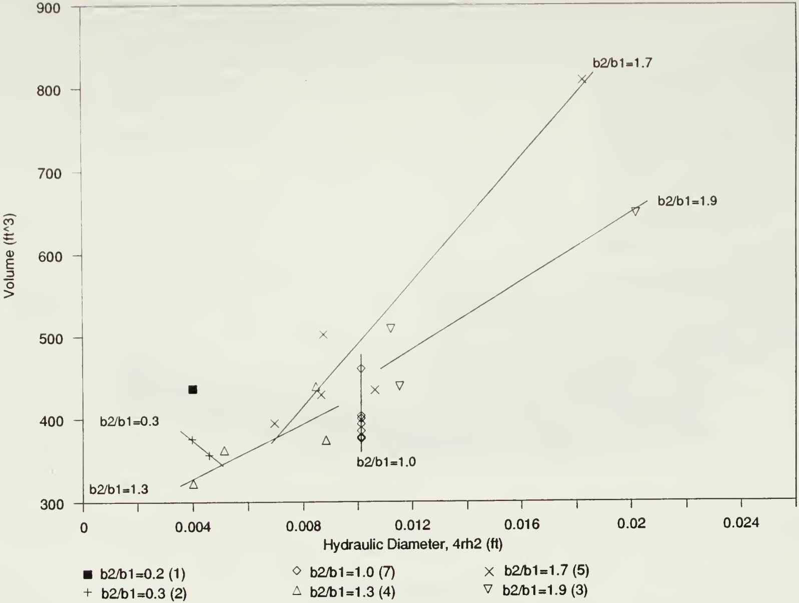


Figure 7a. Volume vs. Hydraulic Diameter. Side One Surface 3/16-11.1: b_1=0.0208 ft, $4r_{h1}$=0.01012 ft

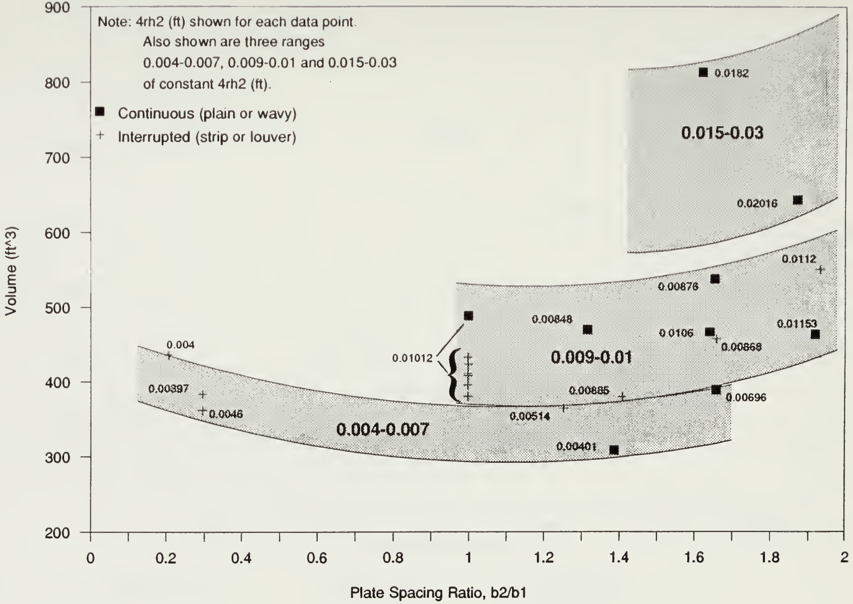


Figure 7b. Volume vs. Plate Spacing Ratio. Side One Surface 3/16-11.1: b_1=0.0208 ft, $4r_{h1}$=0.01012 ft

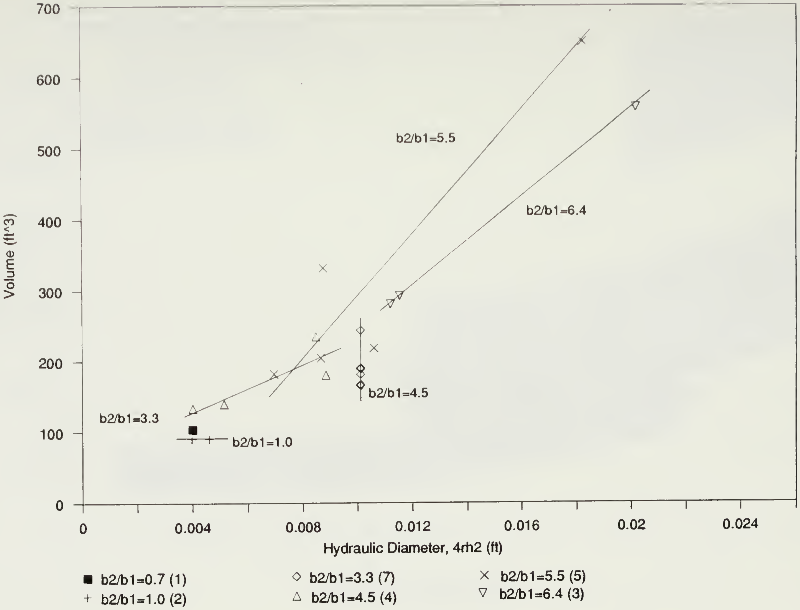


Figure 8a. Volume vs. Hydraulic Diameter. Side One Surface 1/9-24.12: b_1=0.0063 ft, $4r_{h1}$=0.00397 ft

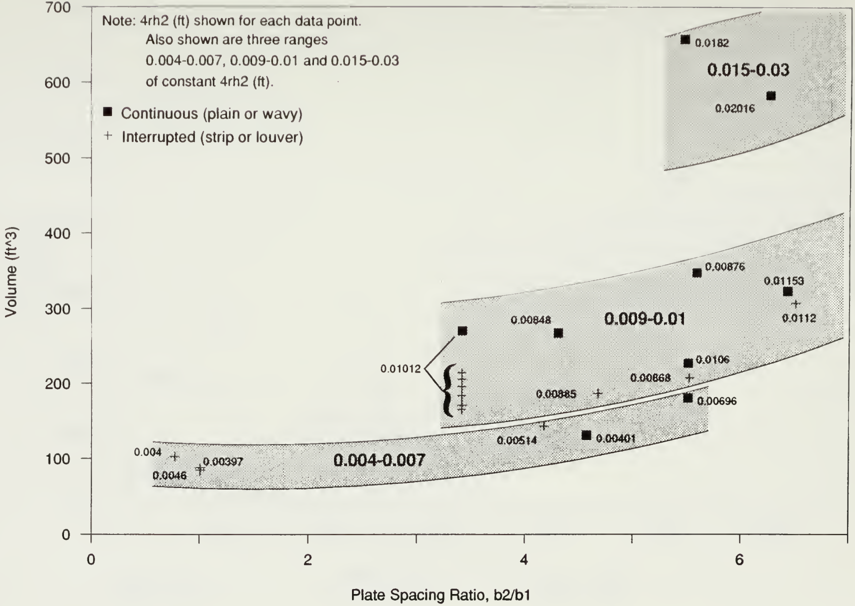


Figure 8b. Volume vs. Plate Spacing Ratio. Side One Surface 1/9-24.12: b_1=0.0063 ft, $4r_{h1}$=0.00397 ft

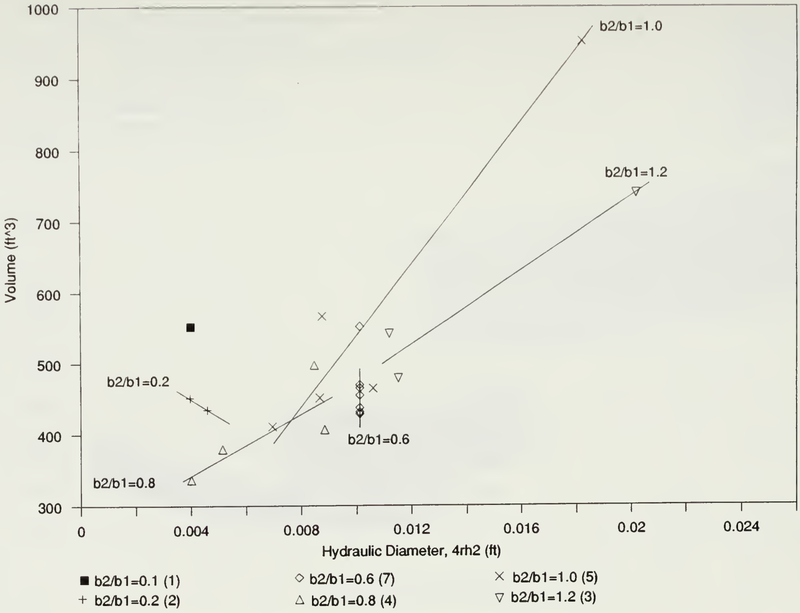


Figure 9a. Volume vs. Hydraulic Diameter. Side One Surface 17.8-3/8W: b_1=0.0345 ft, $4r_{h1}$=0.00696 ft

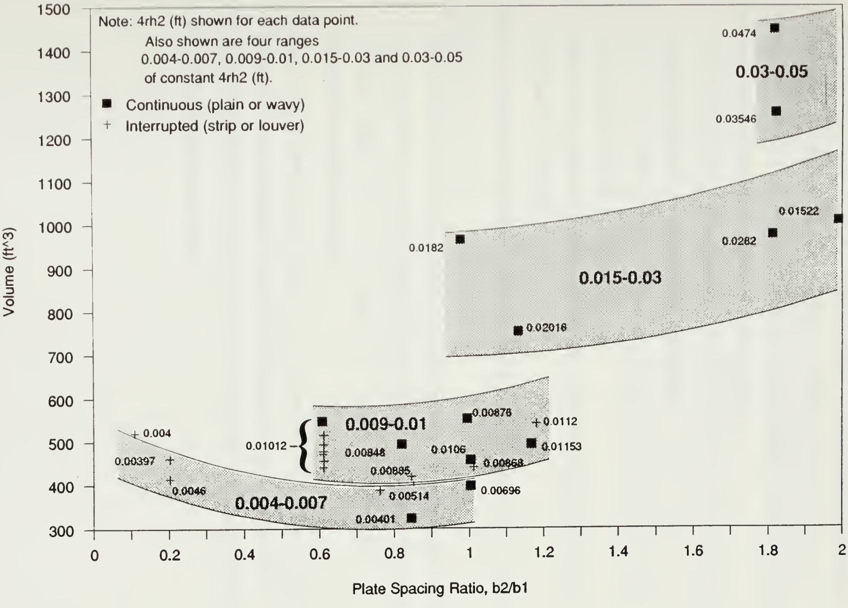


Figure 9b. Volume vs. Plate Spacing Ratio. Side One Surface 17.8-3/8W: b_1=0.0345 ft, $4r_{h1}$=0.00696 ft

5 CONCLUSIONS

Based on the data from Table 3 as plotted in Figure 6, a trend emerges which can be developed into a set of criteria for selecting the pair of "ideally designed" surfaces for minimum heat exchanger core volume. For given operating conditions, the heat exchanger core volume will be minimized by following the below steps:

1. Choose the most narrow plate spacing for the high pressure side (side one) based on constraints such as fabrication difficulty, fouling, etc.
2. List all other available surfaces with plate spacings nearly equal to the high pressure plate spacing (i.e. those with $b_2/b_1 \cong 1.0$).
3. Select from this list the surface for side two which minimizes the ratio K_{f2}/K_{f1} and maximizes the ratio K_{j2}/K_{j1}.

However, for real surfaces, parameters such as K_j and K_f are not readily known. For this reason, the third step should be:

3. Select from this list the surface with the minimum hydraulic diameter for use on side two. If more than one surface meets the above criteria for side two then an interrupted fin surface will generally result in a smaller heat exchanger core volume than a comparable continuous fin surface.

If this three step procedure for real surfaces had been followed for the operating conditions from Section 3 and if no cleaning or fabrication constraints were imposed on the plate spacings then this procedure would result in selecting the identical surface pair that results in the minimum heat exchanger core volume.

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3. Beyer, W. H., CRC Standard Mathematical Tables. 27th Edition, CRC Press, Inc., Boca Raton, FL (1984)

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APPENDIX A

Contained in this appendix are plots of j_n and f_n versus Reynolds Number similar to Figure 4 of the report. Each plot shows the actual data points and a line with slope equal to -0.46 through the points. Also shown is the average error between the data points and the line for each data set.

The average error was determined by finding the absolute values of the differences between the data points and the line. These absolute values were expressed as a percentage of the actual j_n or f_n values and then averaged to find the average error for each data set.

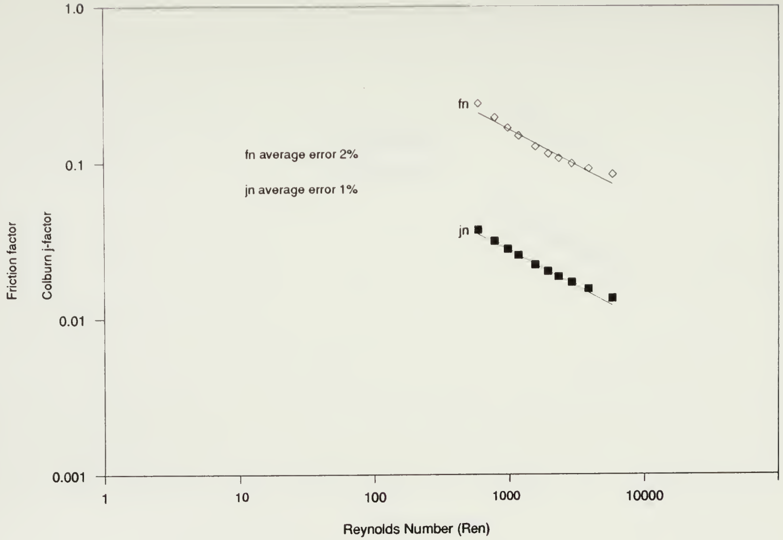

Figure A1. Surface 1/10-19.74 (S27); Slope = -0.46.

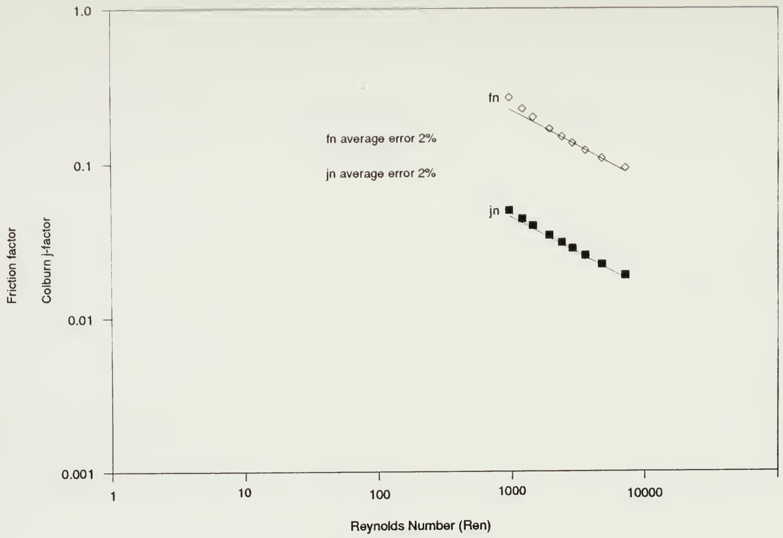

Figure A2. Surface 1/10-19.35 (S29); Slope = -0.46.

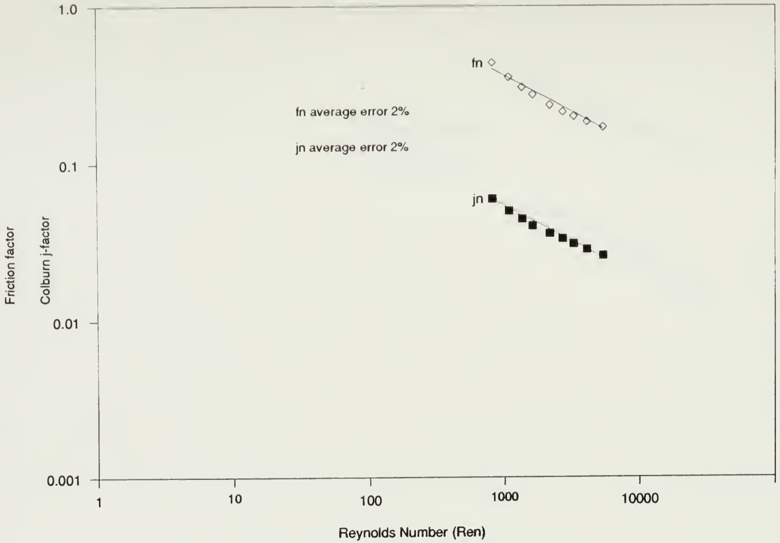

Figure A3. Surface 1/9-24.12 (S28); Slope = -0.46.

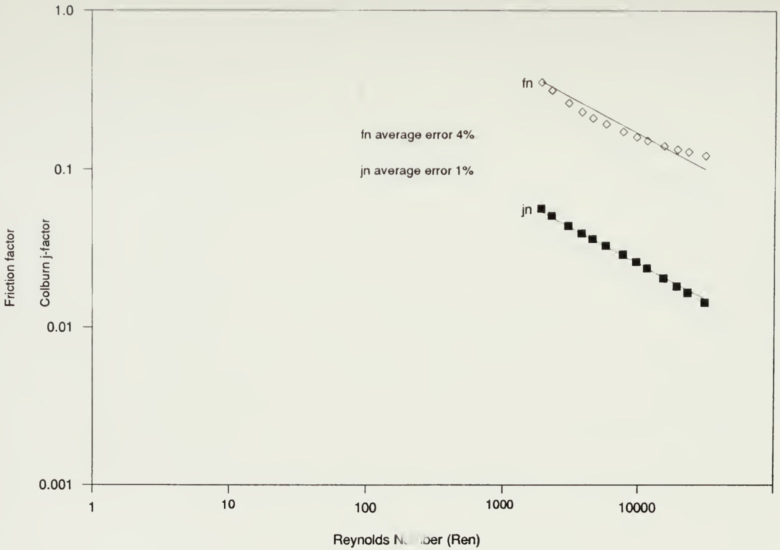

Figure A4. Surface 3/8-11.1 (L19); Slope = -0.46.

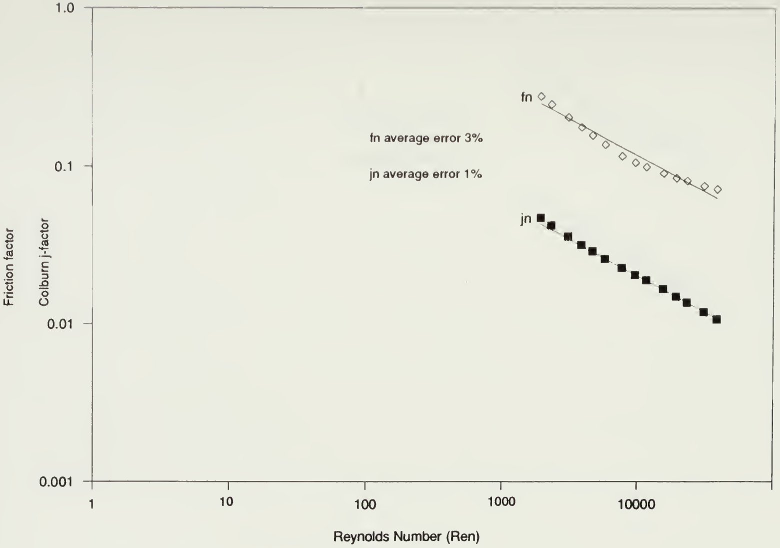

Figure A5. Surface 3/4-11.1 (L21); Slope = -0.46.

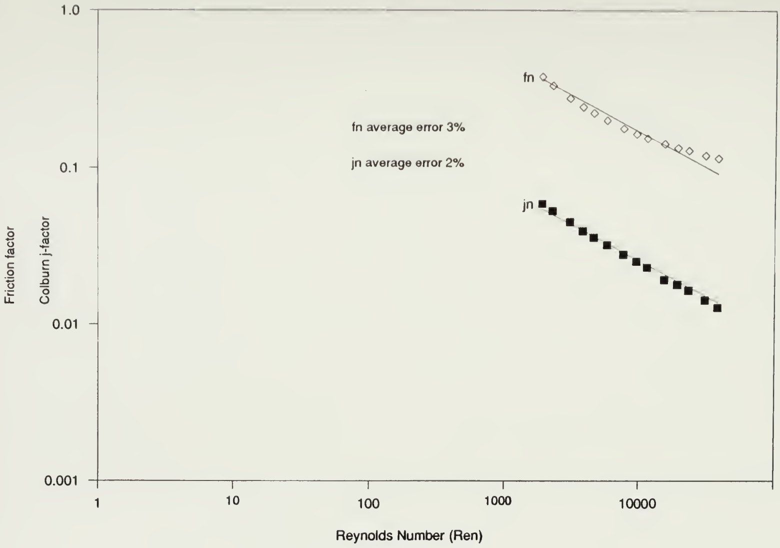

Figure A6. Surface 3/8-11.1 (L18); Slope = -0.46.

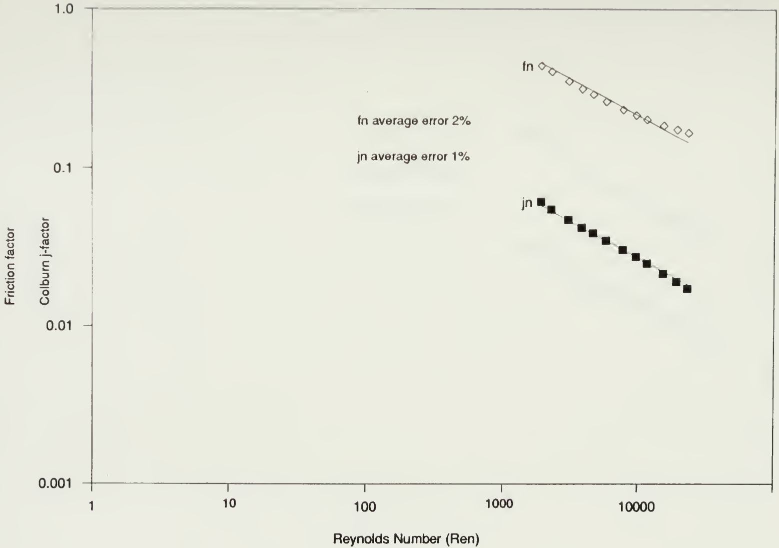

Figure A7. Surface 3/16-11.1 (L15); Slope = -0.46.

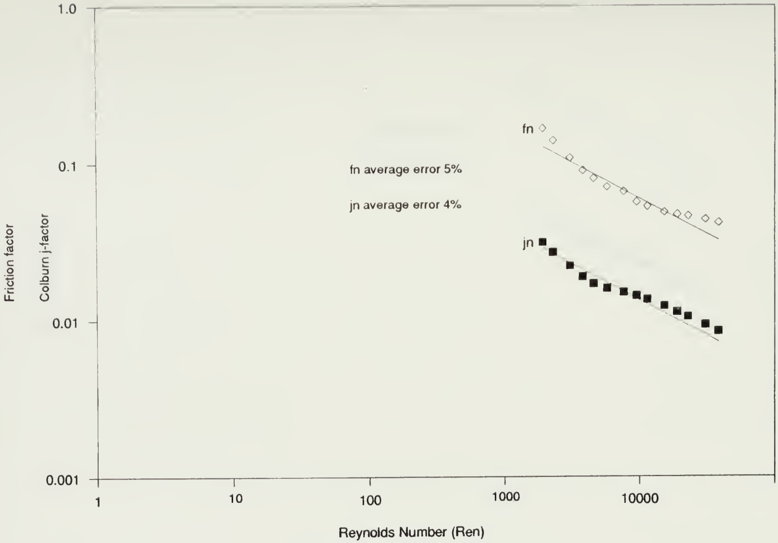

Figure A8. Surface 11.1 (P04); Slope = -0.46.

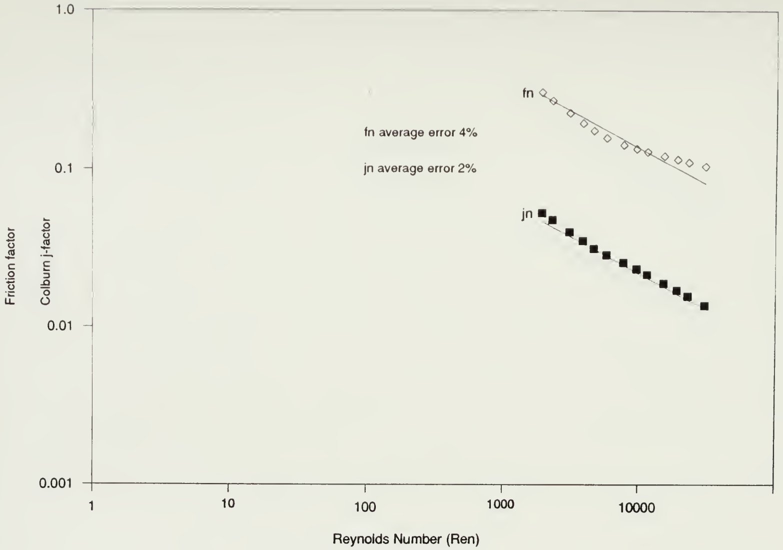

Figure A9. Surface 1/2-11.1 (L20); Slope = -0.46.

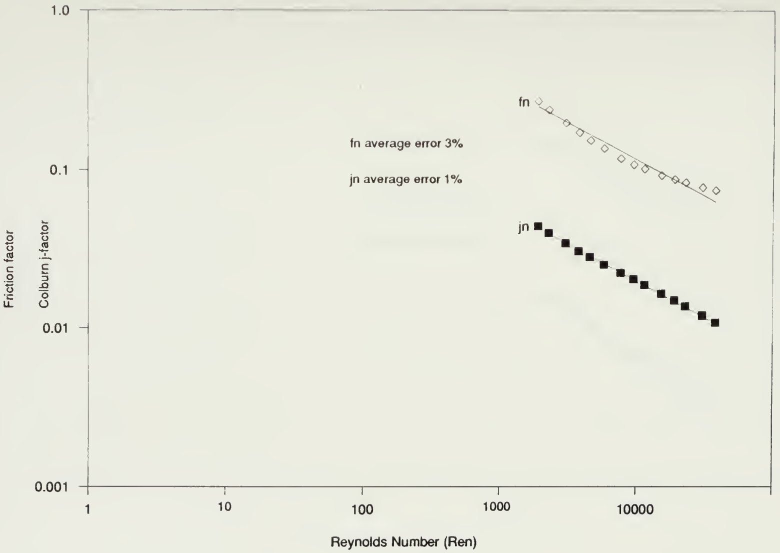

Figure A10. Surface 3/4(b)-11.1 (L22); Slope = -0.46.

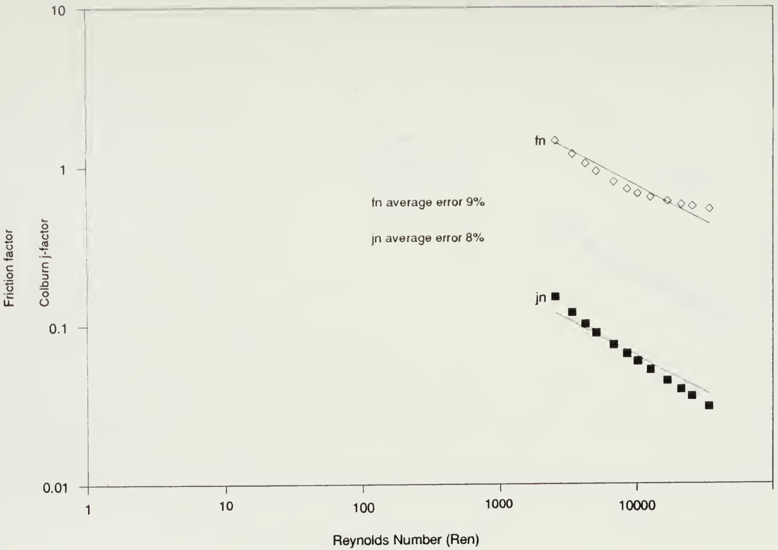

Figure A11. Surface 1/8-16.12T (S31); Slope = -0.46.

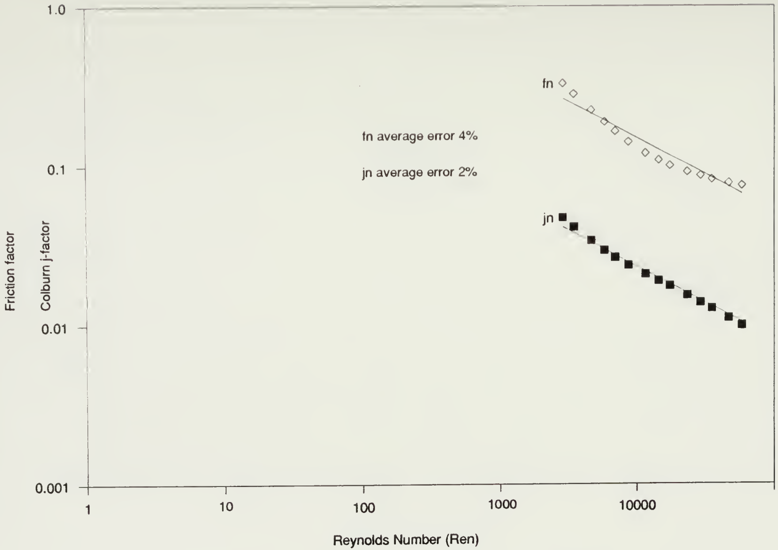

Figure A12. Surface 14.77 (P06); Slope = -0.46.

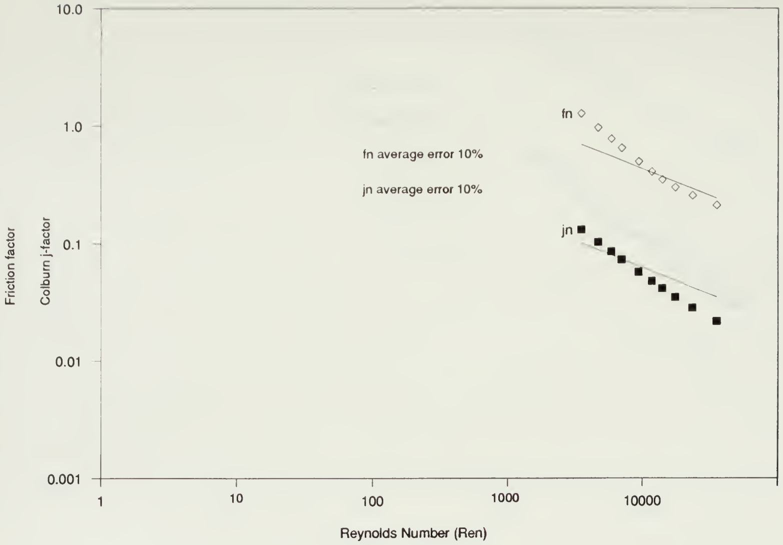

Figure A13. Surface 30.33T (P10); Slope = -0.46.

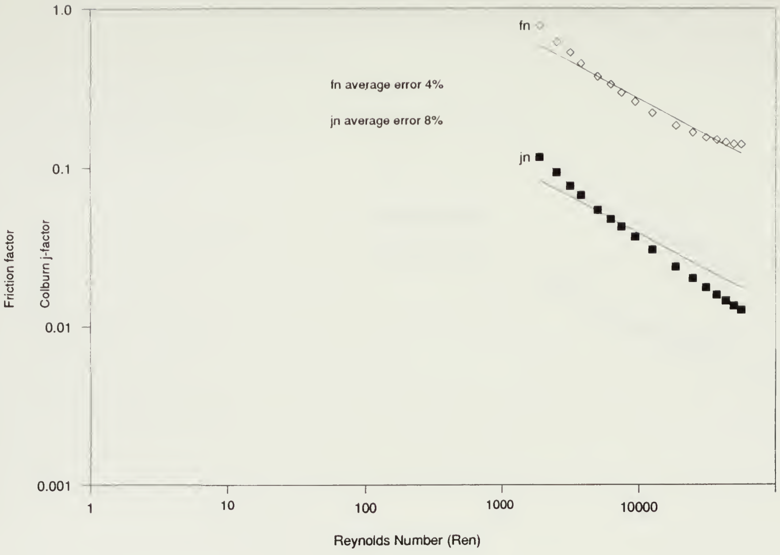

Figure A14. Surface 1/6-12.18D (S30); Slope = -0.46.

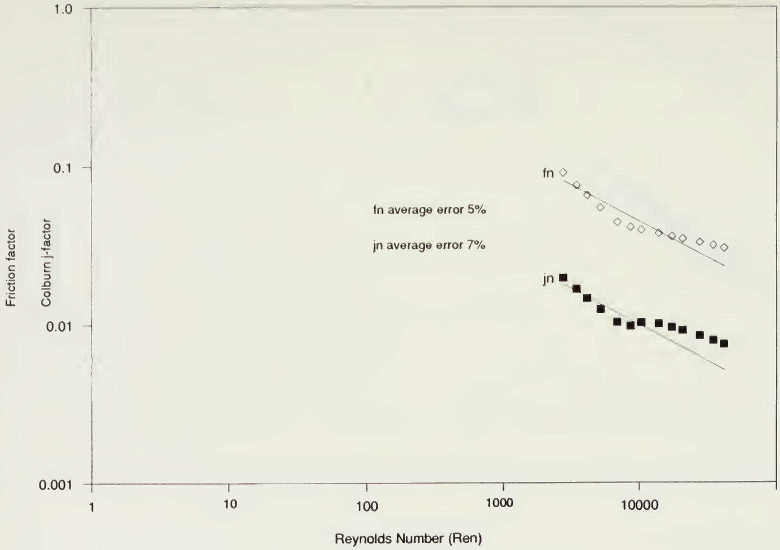

Figure A15. Surface 6.2 (P02); Slope = -0.46.

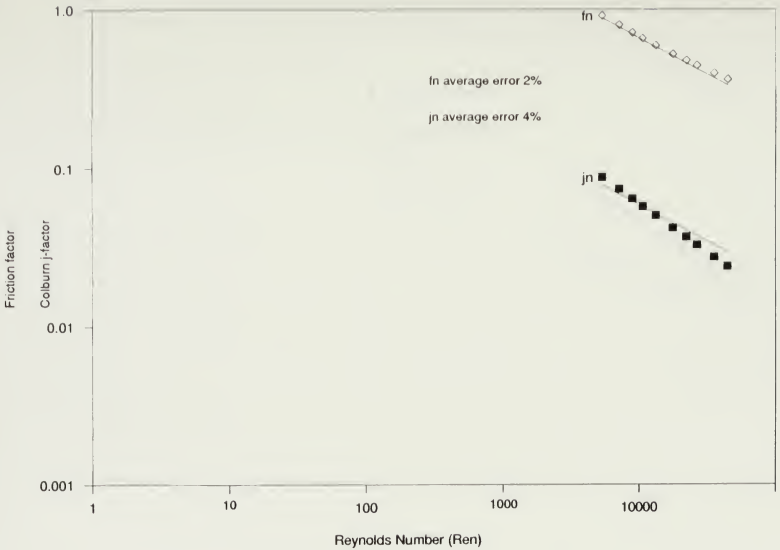

Figure A16. Surface 17.8-3/8W (W27); Slope = -0.46.

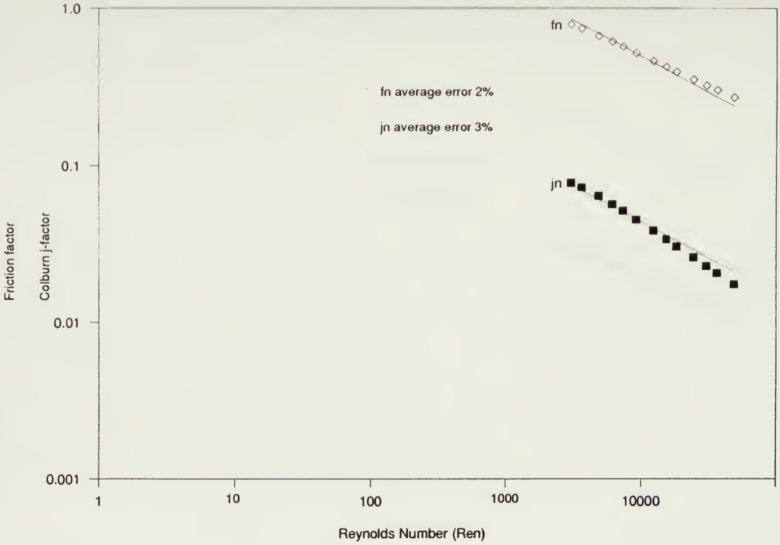

Figure A17. Surface 11.44-3/8W (W26); Slope = -0.46.

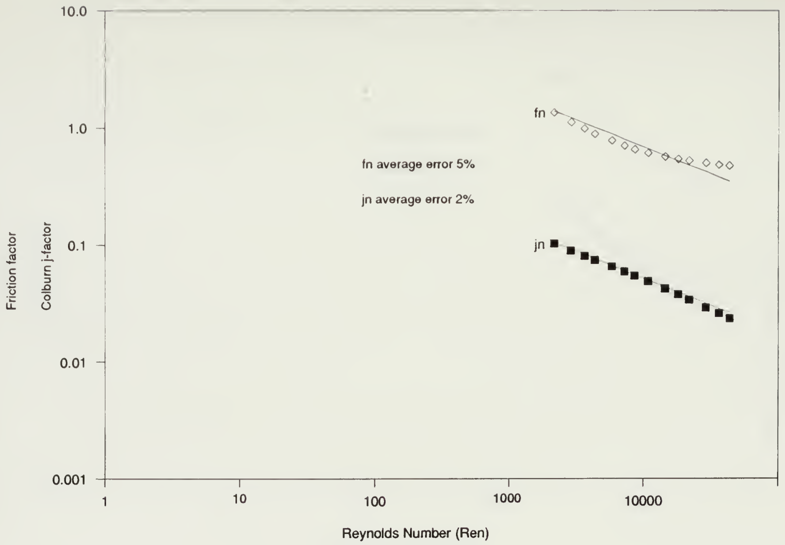

Figure A18. Surface 1/8-15.2 (S25); Slope = -0.46.

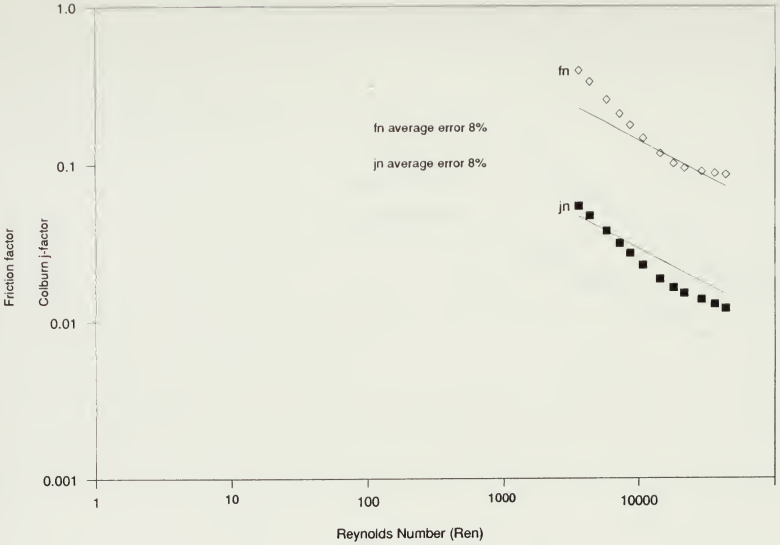

Figure A19. Surface 15.08 (PO7); Slope = -0.46.

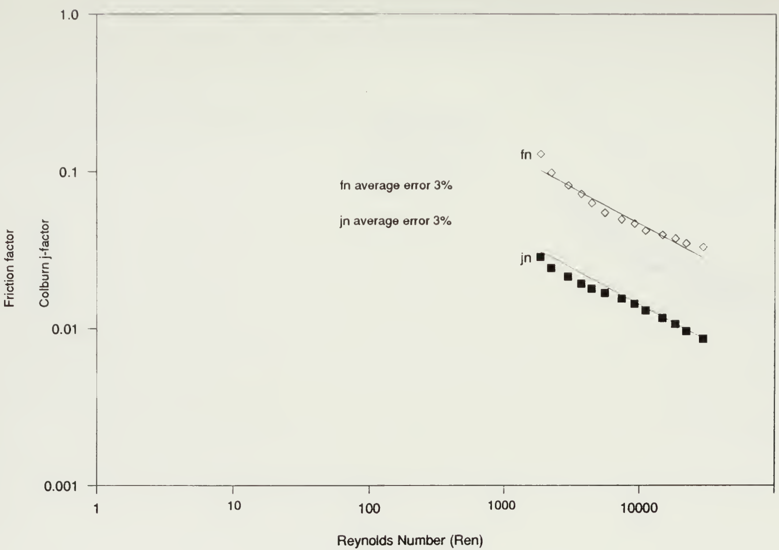

Figure A20. Surface 5.3 (P01); Slope = -0.46.

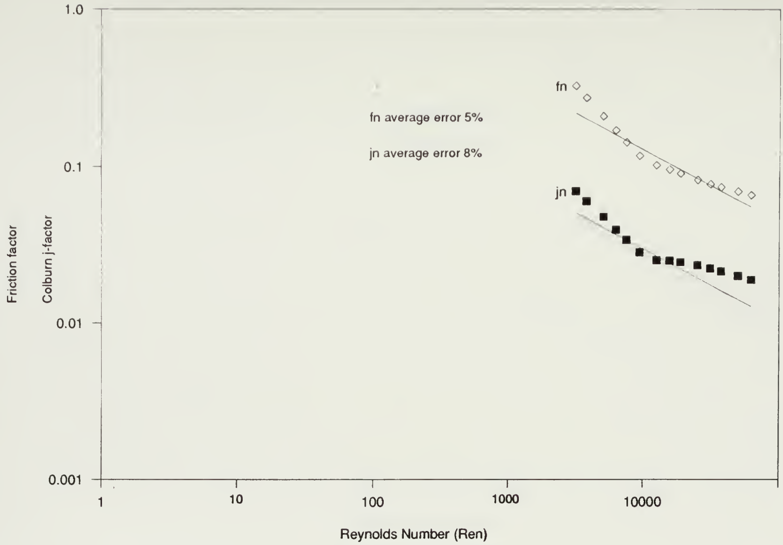

Figure A21. Surface 11.11(a) (P05); Slope = -0.46.

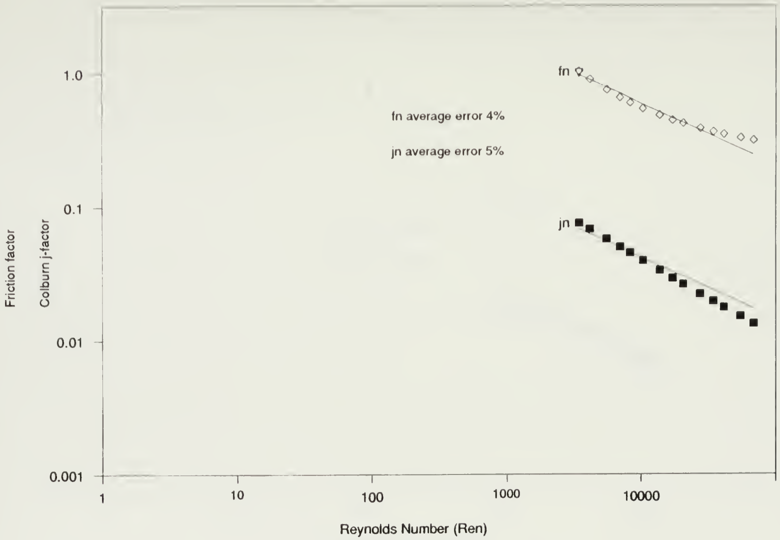

Figure A22. Surface 3/32-12.22 (S24); Slope = -0.46.

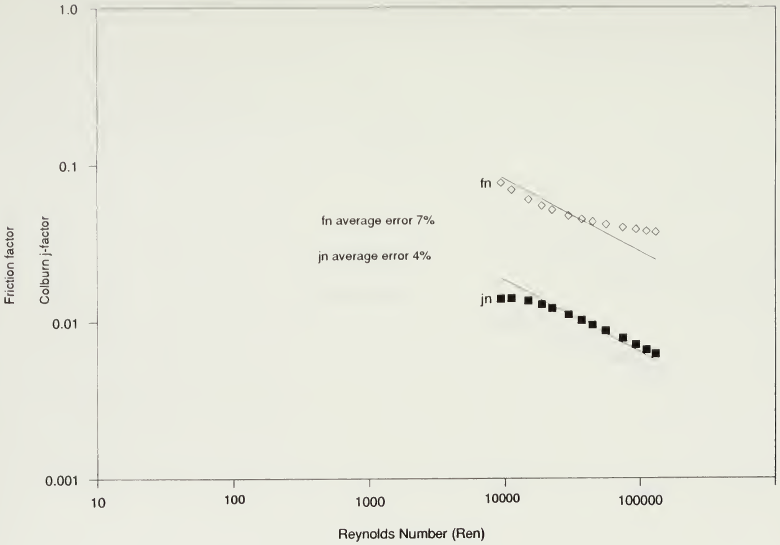

Figure A23. Surface 3.97 (P14); Slope = -0.46.

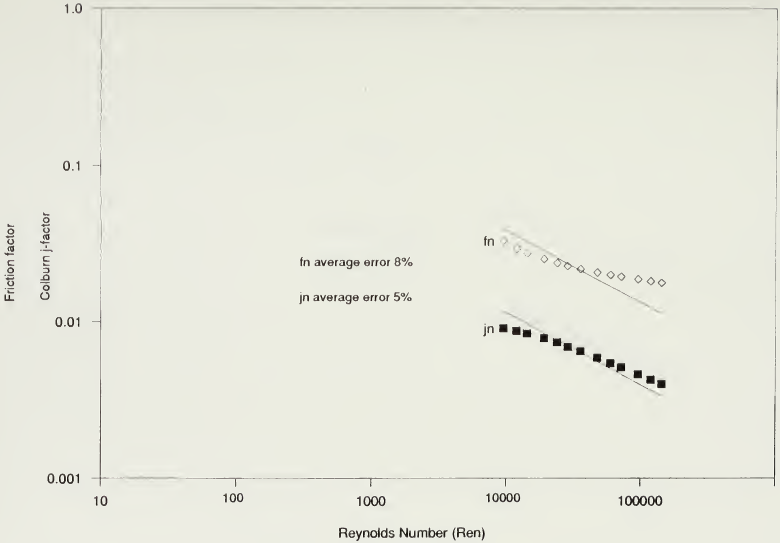

Figure A24. Surface 2.0 (P12); Slope = -0.46.

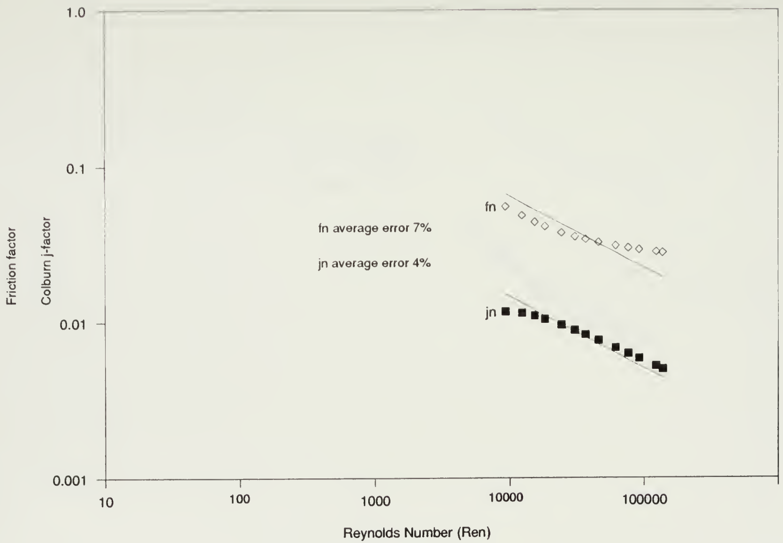

Figure A25. Surface 3.01 (P13); Slope = -0.46.

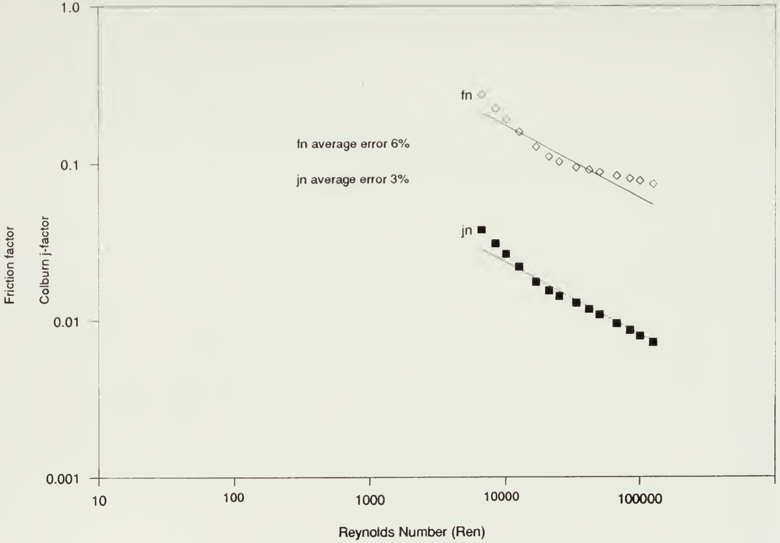

Figure A26. Surface 9.03 (P03); Slope = -0.46.

APPENDIX B

Contained in this appendix are tables similar to Table 3 for each of the 26 K-L surfaces examined in this study. Each table is for a specific surface on the high pressure side (side one) of the heat exchanger. This surface is paired with every other surface and the resulting volumes are tabulated. The operating conditions are the same as those previously specified in Section 3 of the report.

Table B-1. Side One: 1/10-19.74

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	99.8	1.0	1.00	1.00
1/10-19.35	0.00460	92.0	1.5	1.63	1.34
1/9-24.12	0.00397	93.8	1.5	2.00	2.23
3/8(b)-11.1	0.01012	176.5	4.9	2.66	2.95
3/4-11.1	0.01012	196.6	4.9	2.13	2.06
3/8-11.1	0.01012	175.1	4.9	2.70	3.01
3/16-11.1	0.01012	176.8	4.9	2.85	3.77
11.1	0.01012	249.4	4.9	1.42	1.06
1/2-11.1	0.01012	189.7	4.9	2.31	2.41
3/4(b)-11.1	0.01012	198.7	4.9	2.10	2.06
1/8-16.12T	0.00514	158.4	6.2	6.77	13.41
14.77	0.00848	248.2	6.5	2.46	2.65
30.33T	0.00401	150.7	6.8	6.58	7.63
1/6-12.18D	0.00885	196.7	7.0	4.05	4.77
6.2	0.01820	684.1	8.0	1.05	0.79
17.8-3/8W	0.00696	203.7	8.2	6.17	11.65
11.44-3/8W	0.01060	239.0	8.2	4.59	8.70
1/8-15.2	0.00868	226.2	8.2	5.45	12.15
15.08	0.00876	355.1	8.2	2.21	1.79
5.3	0.02016	601.0	9.3	1.50	0.82
11.11(a)	0.01153	320.8	9.5	3.12	2.25
3/32-12.22	0.01120	305.4	9.6	4.42	10.47
3.97	0.02820	1123.4	14.8	1.94	1.43
2.0	0.04740	1914.1	14.8	1.20	0.68
3.01	0.03546	1458.2	14.8	1.53	1.14
9.03	0.01522	1056.8	16.2	2.48	3.08

Table B-2. Side One: 1/10-19.35

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	116.3	0.7	0.61	0.74
1/10-19.35	0.00460	102.8	1.0	1.00	1.00
1/9-24.12	0.00397	104.2	1.0	1.23	1.66
3/8(b)-11.1	0.01012	179.2	3.3	1.63	2.20
3/4-11.1	0.01012	199.3	3.3	1.31	1.53
3/8-11.1	0.01012	177.8	3.3	1.66	2.24
3/16-11.1	0.01012	179.9	3.3	1.75	2.80
11.1	0.01012	250.1	3.3	0.87	0.79
1/2-11.1	0.01012	192.6	3.3	1.42	1.79
3/4(b)-11.1	0.01012	201.5	3.3	1.29	1.53
1/8-16.12T	0.00514	157.1	4.2	4.15	9.99
14.77	0.00848	244.2	4.4	1.51	1.97
30.33T	0.00401	147.6	4.6	4.04	5.68
1/6-12.18D	0.00885	193.0	4.7	2.48	3.55
6.2	0.01820	618.5	5.4	0.64	0.59
17.8-3/8W	0.00696	198.9	5.5	3.79	8.67
11.44-3/8W	0.01060	233.8	5.5	2.82	6.48
1/8-15.2	0.00868	221.8	5.5	3.34	9.04
15.08	0.00876	330.4	5.6	1.35	1.34
5.3	0.02016	526.6	6.3	0.92	0.61
11.11(a)	0.01153	292.3	6.4	1.91	1.68
3/32-12.22	0.01120	295.9	6.5	2.71	7.79
3.97	0.02820	937.8	10.0	1.19	1.06
2.0	0.04740	1575.2	10.0	0.74	0.50
3.01	0.03546	1211.9	10.0	0.94	0.84
9.03	0.01522	894.7	11.0	1.52	2.29

Table B-3. Side One: 1/9-24.12

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	103.5	0.7	0.50	0.45
1/10-19.35	0.00460	90.9	1.0	0.81	0.60
1/9-24.12	0.00397	91.0	1.0	1.00	1.00
3/8(b)-11.1	0.01012	167.1	3.3	1.33	1.32
3/4-11.1	0.01012	188.7	3.3	1.06	0.92
3/8-11.1	0.01012	165.6	3.3	1.35	1.35
3/16-11.1	0.01012	166.8	3.3	1.43	1.69
11.1	0.01012	243.7	3.3	0.71	0.47
1/2-11.1	0.01012	181.3	3.3	1.15	1.08
3/4(b)-11.1	0.01012	190.9	3.3	1.05	0.92
1/8-16.12T	0.00514	139.5	4.2	3.39	6.02
14.77	0.00848	234.8	4.4	1.23	1.19
30.33T	0.00401	132.9	4.6	3.29	3.42
1/6-12.18D	0.00885	180.4	4.7	2.03	2.14
6.2	0.01820	649.6	5.4	0.52	0.35
17.8-3/8W	0.00696	182.1	5.5	3.08	5.22
11.44-3/8W	0.01060	218.5	5.5	2.30	3.90
1/8-15.2	0.00868	204.5	5.5	2.73	5.45
15.08	0.00876	331.5	5.6	1.10	0.80
5.3	0.02016	557.6	6.3	0.75	0.37
11.11(a)	0.01153	292.6	6.4	1.56	1.01
3/32-12.22	0.01120	280.7	6.5	2.21	4.70
3.97	0.02820	1020.9	10.0	0.97	0.64
2.0	0.04740	1752.2	10.0	0.60	0.30
3.01	0.03546	1331.9	10.0	0.77	0.51
9.03	0.01522	959.1	11.0	1.24	1.38

Table B-4. Side One: 3/8(b)-11.1

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	462.2	0.2	0.38	0.34
1/10-19.35	0.00460	378.0	0.3	0.61	0.46
1/9-24.12	0.00397	400.2	0.3	0.75	0.76
3/8(b)-11.1	0.01012	394.6	1.0	1.00	1.00
3/4-11.1	0.01012	416.1	1.0	0.80	0.70
3/8-11.1	0.01012	393.0	1.0	1.02	1.02
3/16-11.1	0.01012	403.5	1.0	1.07	1.28
11.1	0.01012	474.4	1.0	0.53	0.36
1/2-11.1	0.01012	410.2	1.0	0.87	0.82
3/4(b)-11.1	0.01012	419.6	1.0	0.79	0.70
1/8-16.12T	0.00514	384.3	1.3	2.54	4.55
14.77	0.00848	454.8	1.3	0.93	0.90
30.33T	0.00401	340.6	1.4	2.47	2.59
1/6-12.18D	0.00885	391.5	1.4	1.52	1.62
6.2	0.01820	819.6	1.6	0.39	0.27
17.8-3/8W	0.00696	415.2	1.7	2.32	3.95
11.44-3/8W	0.01060	454.9	1.7	1.73	2.95
1/8-15.2	0.00868	450.0	1.7	2.05	4.12
15.08	0.00876	515.9	1.7	0.83	0.61
5.3	0.02016	657.8	1.9	0.57	0.28
11.11(a)	0.01153	452.8	1.9	1.17	0.76
3/32-12.22	0.01120	529.9	1.9	1.66	3.55
3.97	0.02820	921.4	3.0	0.73	0.49
2.0	0.04740	1309.2	3.0	0.45	0.23
3.01	0.03546	1118.8	3.0	0.58	0.38
9.03	0.01522	952.6	3.3	0.93	1.04

Table B-5. Side One: 3/4-11.1

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	559.8	0.2	0.47	0.49
1/10-19.35	0.00460	460.5	0.3	0.77	0.65
1/9-24.12	0.00397	493.3	0.3	0.94	1.08
3/8(b)-11.1	0.01012	458.3	1.0	1.25	1.43
3/4-11.1	0.01012	475.6	1.0	1.00	1.00
3/8-11.1	0.01012	457.0	1.0	1.27	1.46
3/16-11.1	0.01012	471.0	1.0	1.34	1.83
11.1	0.01012	527.2	1.0	0.67	0.51
1/2-11.1	0.01012	471.7	1.0	1.09	1.17
3/4(b)-11.1	0.01012	479.3	1.0	0.99	1.00
1/8-16.12T	0.00514	468.0	1.3	3.18	6.52
14.77	0.00848	514.9	1.3	1.16	1.29
30.33T	0.00401	411.5	1.4	3.09	3.71
1/6-12.18D	0.00885	457.0	1.4	1.90	2.32
6.2	0.01820	867.2	1.6	0.49	0.38
17.8-3/8W	0.00696	493.6	1.7	2.90	5.66
11.44-3/8W	0.01060	529.8	1.7	2.16	4.23
1/8-15.2	0.00868	530.4	1.7	2.56	5.91
15.08	0.00876	569.7	1.7	1.04	0.87
5.3	0.02016	702.1	1.9	0.71	0.40
11.11(a)	0.01153	506.8	1.9	1.47	1.10
3/32-12.22	0.01120	608.5	1.9	2.08	5.09
3.97	0.02820	965.9	3.0	0.91	0.70
2.0	0.04740	1330.5	3.0	0.57	0.33
3.01	0.03546	1157.2	3.0	0.72	0.55
9.03	0.01522	1010.9	3.3	1.16	1.50

Table B-6. Side One: 3/8-11.1

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	456.4	0.2	0.37	0.33
1/10-19.35	0.00460	373.1	0.3	0.60	0.45
1/9-24.12	0.00397	394.6	0.3	0.74	0.74
3/8(b)-11.1	0.01012	390.8	1.0	0.98	0.98
3/4-11.1	0.01012	412.5	1.0	0.79	0.68
3/8-11.1	0.01012	389.1	1.0	1.00	1.00
3/16-11.1	0.01012	399.4	1.0	1.06	1.25
11.1	0.01012	471.3	1.0	0.53	0.35
1/2-11.1	0.01012	406.5	1.0	0.85	0.80
3/4(b)-11.1	0.01012	416.0	1.0	0.78	0.68
1/8-16.12T	0.00514	379.3	1.3	2.50	4.45
14.77	0.00848	451.2	1.3	0.91	0.88
30.33T	0.00401	336.4	1.4	2.43	2.53
1/6-12.18D	0.00885	387.6	1.4	1.50	1.58
6.2	0.01820	816.8	1.6	0.39	0.26
17.8-3/8W	0.00696	410.5	1.7	2.28	3.87
11.44-3/8W	0.01060	450.4	1.7	1.70	2.89
1/8-15.2	0.00868	445.2	1.7	2.02	4.03
15.08	0.00876	512.6	1.7	0.82	0.60
5.3	0.02016	655.1	1.9	0.56	0.27
11.11(a)	0.01153	449.5	1.9	1.15	0.75
3/32-12.22	0.01120	525.2	1.9	1.63	3.48
3.97	0.02820	918.7	3.0	0.72	0.47
2.0	0.04740	1308.1	3.0	0.45	0.22
3.01	0.03546	1116.6	3.0	0.57	0.38
9.03	0.01522	949.1	3.3	0.92	1.02

Table B-7. Side One: 3/16-11.1					
Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	436.7	0.2	0.35	0.27
1/10-19.35	0.00460	356.4	0.3	0.57	0.36
1/9-24.12	0.00397	375.8	0.3	0.70	0.59
3/8(b)-11.1	0.01012	377.9	1.0	0.93	0.78
3/4-11.1	0.01012	400.5	1.0	0.75	0.55
3/8-11.1	0.01012	376.2	1.0	0.95	0.80
3/16-11.1	0.01012	385.8	1.0	1.00	1.00
11.1	0.01012	460.7	1.0	0.50	0.28
1/2-11.1	0.01012	394.1	1.0	0.81	0.64
3/4(b)-11.1	0.01012	404.0	1.0	0.74	0.55
1/8-16.12T	0.00514	362.4	1.3	2.37	3.56
14.77	0.00848	439.1	1.3	0.86	0.70
30.33T	0.00401	322.1	1.4	2.30	2.03
1/6-12.18D	0.00885	374.4	1.4	1.42	1.27
6.2	0.01820	809.1	1.6	0.37	0.21
17.8-3/8W	0.00696	394.7	1.7	2.16	3.09
11.44-3/8W	0.01060	435.3	1.7	1.61	2.31
1/8-15.2	0.00868	429.0	1.7	1.91	3.22
15.08	0.00876	502.2	1.7	0.77	0.48
5.3	0.02016	648.5	1.9	0.53	0.22
11.11(a)	0.01153	439.2	1.9	1.09	0.60
3/32-12.22	0.01120	509.3	1.9	1.55	2.78
3.97	0.02820	916.8	3.0	0.68	0.38
2.0	0.04740	1321.9	3.0	0.42	0.18
3.01	0.03546	1119.3	3.0	0.54	0.30
9.03	0.01522	942.0	3.3	0.87	0.82

Table B-8. Side One: 11.1

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	817.1	0.2	0.70	0.95
1/10-19.35	0.00460	678.6	0.3	1.15	1.27
1/9-24.12	0.00397	740.3	0.3	1.41	2.11
3/8(b)-11.1	0.01012	624.6	1.0	1.87	2.79
3/4-11.1	0.01012	630.3	1.0	1.50	1.95
3/8-11.1	0.01012	623.9	1.0	1.90	2.85
3/16-11.1	0.01012	647.4	1.0	2.01	3.57
11.1	0.01012	663.4	1.0	1.00	1.00
1/2-11.1	0.01012	631.5	1.0	1.62	2.28
3/4(b)-11.1	0.01012	634.1	1.0	1.48	1.95
1/8-16.12T	0.00514	689.2	1.3	4.76	12.70
14.77	0.00848	670.6	1.3	1.73	2.50
30.33T	0.00401	598.7	1.4	4.63	7.22
1/6-12.18D	0.00885	628.2	1.4	2.85	4.51
6.2	0.01820	991.7	1.6	0.74	0.75
17.8-3/8W	0.00696	699.5	1.7	4.34	11.02
11.44-3/8W	0.01060	725.3	1.7	3.23	8.24
1/8-15.2	0.00868	740.8	1.7	3.83	11.50
15.08	0.00876	708.9	1.7	1.55	1.70
5.3	0.02016	819.2	1.9	1.06	0.78
11.11(a)	0.01153	647.1	1.9	2.20	2.13
3/32-12.22	0.01120	813.0	1.9	3.11	9.91
3.97	0.02820	1092.4	3.0	1.37	1.35
2.0	0.04740	1420.5	3.0	0.85	0.64
3.01	0.03546	1275.0	3.0	1.08	1.07
9.03	0.01522	1168.2	3.3	1.74	2.91

Table B-9. Side One: 1/2-11.1

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	521.2	0.2	0.43	0.42
1/10-19.35	0.00460	427.8	0.3	0.71	0.56
1/9-24.12	0.00397	456.4	0.3	0.87	0.93
3/8(b)-11.1	0.01012	433.2	1.0	1.15	1.23
3/4-11.1	0.01012	452.2	1.0	0.92	0.85
3/8-11.1	0.01012	431.7	1.0	1.17	1.25
3/16-11.1	0.01012	444.4	1.0	1.24	1.56
11.1	0.01012	506.5	1.0	0.62	0.44
1/2-11.1	0.01012	447.4	1.0	1.00	1.00
3/4(b)-11.1	0.01012	455.8	1.0	0.91	0.86
1/8-16.12T	0.00514	434.8	1.3	2.93	5.57
14.77	0.00848	491.2	1.3	1.07	1.10
30.33T	0.00401	383.5	1.4	2.85	3.17
1/6-12.18D	0.00885	431.2	1.4	1.75	1.98
6.2	0.01820	848.6	1.6	0.45	0.33
17.8-3/8W	0.00696	462.6	1.7	2.67	4.84
11.44-3/8W	0.01060	500.2	1.7	1.99	3.61
1/8-15.2	0.00868	498.6	1.7	2.36	5.05
15.08	0.00876	548.5	1.7	0.96	0.75
5.3	0.02016	684.8	1.9	0.65	0.34
11.11(a)	0.01153	485.5	1.9	1.35	0.94
3/32-12.22	0.01120	577.5	1.9	1.91	4.35
3.97	0.02820	948.7	3.0	0.84	0.59
2.0	0.04740	1322.8	3.0	0.52	0.28
3.01	0.03546	1142.5	3.0	0.66	0.47
9.03	0.01522	988.2	3.3	1.07	1.28

Table B-10. Side One: 3/4(b)-11.1

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	565.5	0.2	0.48	0.49
1/10-19.35	0.00460	465.4	0.3	0.77	0.65
1/9-24.12	0.00397	498.8	0.3	0.95	1.08
3/8(b)-11.1	0.01012	462.1	1.0	1.27	1.43
3/4-11.1	0.01012	479.2	1.0	1.01	1.00
3/8-11.1	0.01012	460.7	1.0	1.29	1.46
3/16-11.1	0.01012	475.0	1.0	1.36	1.83
11.1	0.01012	530.4	1.0	0.68	0.51
1/2-11.1	0.01012	475.3	1.0	1.10	1.17
3/4(b)-11.1	0.01012	482.8	1.0	1.00	1.00
1/8-16.12T	0.00514	472.9	1.3	3.22	6.52
14.77	0.00848	518.4	1.3	1.17	1.29
30.33T	0.00401	415.8	1.4	3.13	3.71
1/6-12.18D	0.00885	460.9	1.4	1.93	2.32
6.2	0.01820	870.2	1.6	0.50	0.38
17.8-3/8W	0.00696	498.3	1.7	2.93	5.66
11.44-3/8W	0.01060	534.2	1.7	2.18	4.23
1/8-15.2	0.00868	535.1	1.7	2.59	5.90
15.08	0.00876	572.9	1.7	1.05	0.87
5.3	0.02016	704.9	1.9	0.72	0.40
11.11(a)	0.01153	510.0	1.9	1.48	1.09
3/32-12.22	0.01120	613.2	1.9	2.10	5.09
3.97	0.02820	969.2	3.0	0.92	0.70
2.0	0.04740	1333.7	3.0	0.57	0.33
3.01	0.03546	1160.6	3.0	0.73	0.55
9.03	0.01522	1014.8	3.3	1.18	1.49

Table B-11. Side One: 1/8-16.12T

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	337.6	0.2	0.15	0.07
1/10-19.35	0.00460	266.8	0.2	0.24	0.10
1/9-24.12	0.00397	270.5	0.2	0.30	0.17
3/8(b)-11.1	0.01012	307.4	0.8	0.39	0.22
3/4-11.1	0.01012	339.9	0.8	0.31	0.15
3/8-11.1	0.01012	305.1	0.8	0.40	0.22
3/16-11.1	0.01012	309.5	0.8	0.42	0.28
11.1	0.01012	419.5	0.8	0.21	0.08
1/2-11.1	0.01012	329.4	0.8	0.34	0.18
3/4(b)-11.1	0.01012	343.6	0.8	0.31	0.15
1/8-16.12T	0.00514	252.8	1.0	1.00	1.00
14.77	0.00848	376.2	1.1	0.36	0.20
30.33T	0.00401	229.1	1.1	0.97	0.57
1/6-12.18D	0.00885	294.6	1.1	0.60	0.36
6.2	0.01820	802.0	1.3	0.15	0.06
17.8-3/8W	0.00696	292.2	1.3	0.91	0.87
11.44-3/8W	0.01060	341.7	1.3	0.68	0.65
1/8-15.2	0.00868	325.6	1.3	0.81	0.91
15.08	0.00876	451.5	1.3	0.33	0.13
5.3	0.02016	627.3	1.5	0.22	0.06
11.11(a)	0.01153	379.6	1.5	0.46	0.17
3/32-12.22	0.01120	411.8	1.5	0.65	0.78
3.97	0.02820	904.0	2.4	0.29	0.11
2.0	0.04740	1391.8	2.4	0.18	0.05
3.01	0.03546	1135.7	2.4	0.23	0.08
9.03	0.01522	899.3	2.6	0.37	0.23

Table B-12. Side One: 14.77

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	800.4	0.2	0.41	0.38
1/10-19.35	0.00460	650.3	0.2	0.66	0.51
1/9-24.12	0.00397	701.0	0.2	0.81	0.84
3/8(b)-11.1	0.01012	586.1	0.8	1.08	1.11
3/4-11.1	0.01012	602.4	0.8	0.86	0.78
3/8-11.1	0.01012	584.7	0.8	1.10	1.14
3/16-11.1	0.01012	604.0	0.8	1.16	1.42
11.1	0.01012	656.3	0.8	0.58	0.40
1/2-11.1	0.01012	599.5	0.8	0.94	0.91
3/4(b)-11.1	0.01012	606.7	0.8	0.85	0.78
1/8-16.12T	0.00514	605.1	0.9	2.75	5.07
14.77	0.00848	635.8	1.0	1.00	1.00
30.33T	0.00401	526.3	1.0	2.67	2.88
1/6-12.18D	0.00885	572.1	1.1	1.64	1.80
6.2	0.01820	1010.5	1.2	0.42	0.30
17.8-3/8W	0.00696	617.7	1.3	2.50	4.40
11.44-3/8W	0.01060	655.1	1.3	1.87	3.29
1/8-15.2	0.00868	660.3	1.3	2.21	4.59
15.08	0.00876	681.3	1.3	0.90	0.68
5.3	0.02016	813.8	1.4	0.61	0.31
11.11(a)	0.01153	605.4	1.5	1.27	0.85
3/32-12.22	0.01120	738.4	1.5	1.79	3.96
3.97	0.02820	1072.0	2.3	0.79	0.54
2.0	0.04740	1438.1	2.3	0.49	0.26
3.01	0.03546	1271.2	2.3	0.62	0.43
9.03	0.01522	1127.6	2.5	1.01	1.16

Table B-13. Side One: 30.33T

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	396.1	0.1	0.15	0.13
1/10-19.35	0.00460	312.6	0.2	0.25	0.18
1/9-24.12	0.00397	319.5	0.2	0.30	0.29
3/8(b)-11.1	0.01012	342.0	0.7	0.40	0.39
3/4-11.1	0.01012	375.2	0.7	0.32	0.27
3/8-11.1	0.01012	339.7	0.7	0.41	0.39
3/16-11.1	0.01012	345.3	0.7	0.43	0.49
11.1	0.01012	456.7	0.7	0.22	0.14
1/2-11.1	0.01012	364.7	0.7	0.35	0.32
3/4(b)-11.1	0.01012	379.1	0.7	0.32	0.27
1/8-16.12T	0.00514	287.7	0.9	1.03	1.76
14.77	0.00848	410.1	1.0	0.37	0.35
30.33T	0.00401	258.7	1.0	1.00	1.00
1/6-12.18D	0.00885	325.7	1.0	0.62	0.63
6.2	0.01820	836.7	1.2	0.16	0.10
17.8-3/8W	0.00696	325.2	1.2	0.94	1.53
11.44-3/8W	0.01060	375.9	1.2	0.70	1.14
1/8-15.2	0.00868	360.6	1.2	0.83	1.59
15.08	0.00876	481.9	1.2	0.34	0.24
5.3	0.02016	649.2	1.4	0.23	0.11
11.11(a)	0.01153	405.4	1.4	0.47	0.30
3/32-12.22	0.01120	448.1	1.4	0.67	1.37
3.97	0.02820	898.9	2.2	0.30	0.19
2.0	0.04740	1327.4	2.2	0.18	0.09
3.01	0.03546	1114.5	2.2	0.23	0.15
9.03	0.01522	910.1	2.4	0.38	0.40

Table B-14. Side One: 1/6-12.18D

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	584.9	0.1	0.25	0.21
1/10-19.35	0.00460	468.2	0.2	0.40	0.28
1/9-24.12	0.00397	493.6	0.2	0.49	0.47
3/8(b)-11.1	0.01012	454.6	0.7	0.66	0.62
3/4-11.1	0.01012	481.8	0.7	0.53	0.43
3/8-11.1	0.01012	452.6	0.7	0.67	0.63
3/16-11.1	0.01012	464.2	0.7	0.70	0.79
11.1	0.01012	554.0	0.7	0.35	0.22
1/2-11.1	0.01012	474.1	0.7	0.57	0.50
3/4(b)-11.1	0.01012	486.0	0.7	0.52	0.43
1/8-16.12T	0.00514	427.4	0.9	1.67	2.81
14.77	0.00848	515.5	0.9	0.61	0.55
30.33T	0.00401	376.6	1.0	1.62	1.60
1/6-12.18D	0.00885	437.0	1.0	1.00	1.00
6.2	0.01820	926.7	1.1	0.26	0.17
17.8-3/8W	0.00696	454.5	1.2	1.52	2.44
11.44-3/8W	0.01060	501.3	1.2	1.13	1.82
1/8-15.2	0.00868	493.9	1.2	1.35	2.55
15.08	0.00876	576.2	1.2	0.54	0.38
5.3	0.02016	729.9	1.3	0.37	0.17
11.11(a)	0.01153	497.4	1.4	0.77	0.47
3/32-12.22	0.01120	578.9	1.4	1.09	2.20
3.97	0.02820	979.5	2.1	0.48	0.30
2.0	0.04740	1377.2	2.1	0.30	0.14
3.01	0.03546	1188.0	2.1	0.38	0.24
9.03	0.01522	1010.8	2.3	0.61	0.64

Table B-15. Side One: 6.2

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	2857.7	0.1	0.96	1.27
1/10-19.35	0.00460	2343.3	0.2	1.56	1.70
1/9-24.12	0.00397	2619.7	0.2	1.91	2.83
3/8(b)-11.1	0.01012	1705.1	0.6	2.54	3.74
3/4-11.1	0.01012	1643.8	0.6	2.03	2.61
3/8-11.1	0.01012	1708.3	0.6	2.58	3.82
3/16-11.1	0.01012	1791.2	0.6	2.73	4.78
11.1	0.01012	1578.3	0.6	1.36	1.34
1/2-11.1	0.01012	1675.5	0.6	2.21	3.05
3/4(b)-11.1	0.01012	1649.8	0.6	2.01	2.61
1/8-16.12T	0.00514	2052.9	0.8	6.47	17.00
14.77	0.00848	1642.6	0.8	2.35	3.35
30.33T	0.00401	1733.8	0.9	6.29	9.67
1/6-12.18D	0.00885	1668.5	0.9	3.87	6.05
6.2	0.01820	1830.3	1.0	1.00	1.00
17.8-3/8W	0.00696	1908.4	1.0	5.90	14.76
11.44-3/8W	0.01060	1878.3	1.0	4.39	11.03
1/8-15.2	0.00868	1977.7	1.0	5.21	15.40
15.08	0.00876	1555.7	1.0	2.11	2.27
5.3	0.02016	1560.2	1.2	1.44	1.04
11.11(a)	0.01153	1467.0	1.2	2.98	2.86
3/32-12.22	0.01120	1987.0	1.2	4.22	13.27
3.97	0.02820	1863.4	1.9	1.86	1.81
2.0	0.04740	2144.0	1.9	1.15	0.86
3.01	0.03546	2051.8	1.9	1.47	1.44
9.03	0.01522	2058.8	2.0	2.37	3.90

Table B-16. Side One: 17.8-3/8W

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{j2}/K_{j1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	552.0	0.1	0.16	0.09
1/10-19.35	0.00460	435.3	0.2	0.26	0.12
1/9-24.12	0.00397	451.8	0.2	0.32	0.19
3/8(b)-11.1	0.01012	431.7	0.6	0.43	0.25
3/4-11.1	0.01012	465.9	0.6	0.34	0.18
3/8-11.1	0.01012	429.2	0.6	0.44	0.26
3/16-11.1	0.01012	438.2	0.6	0.46	0.32
11.1	0.01012	552.3	0.6	0.23	0.09
1/2-11.1	0.01012	455.5	0.6	0.37	0.21
3/4(b)-11.1	0.01012	470.4	0.6	0.34	0.18
1/8-16.12T	0.00514	379.7	0.8	1.10	1.15
14.77	0.00848	498.3	0.8	0.40	0.23
30.33T	0.00401	336.7	0.8	1.07	0.66
1/6-12.18D	0.00885	406.9	0.9	0.66	0.41
6.2	0.01820	952.1	1.0	0.17	0.07
17.8-3/8W	0.00696	411.6	1.0	1.00	1.00
11.44-3/8W	0.01060	465.1	1.0	0.75	0.75
1/8-15.2	0.00868	451.9	1.0	0.88	1.04
15.08	0.00876	566.5	1.0	0.36	0.15
5.3	0.02016	739.2	1.1	0.24	0.07
11.11(a)	0.01153	479.5	1.2	0.51	0.19
3/32-12.22	0.01120	542.4	1.2	0.72	0.90
3.97	0.02820	991.9	1.8	0.31	0.12
2.0	0.04740	1437.3	1.8	0.20	0.06
3.01	0.03546	1218.7	1.8	0.25	0.10
9.03	0.01522	1008.1	2.0	0.40	0.26

Table B-17. Side One: 11.44-3/8W

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	692.1	0.1	0.22	0.11
1/10-19.35	0.00460	550.4	0.2	0.35	0.15
1/9-24.12	0.00397	581.4	0.2	0.44	0.26
3/8(b)-11.1	0.01012	511.3	0.6	0.58	0.34
3/4-11.1	0.01012	540.6	0.6	0.46	0.24
3/8-11.1	0.01012	509.1	0.6	0.59	0.35
3/16-11.1	0.01012	522.4	0.6	0.62	0.43
11.1	0.01012	619.2	0.6	0.31	0.12
1/2-11.1	0.01012	532.5	0.6	0.50	0.28
3/4(b)-11.1	0.01012	545.3	0.6	0.46	0.24
1/8-16.12T	0.00514	479.9	0.8	1.47	1.54
14.77	0.00848	571.4	0.8	0.54	0.30
30.33T	0.00401	420.8	0.8	1.43	0.88
1/6-12.18D	0.00885	485.2	0.9	0.88	0.55
6.2	0.01820	1010.6	1.0	0.23	0.09
17.8-3/8W	0.00696	502.9	1.0	1.34	1.34
11.44-3/8W	0.01060	552.9	1.0	1.00	1.00
1/8-15.2	0.00868	545.7	1.0	1.19	1.40
15.08	0.00876	630.8	1.0	0.48	0.21
5.3	0.02016	792.8	1.1	0.33	0.09
11.11(a)	0.01153	542.7	1.2	0.68	0.26
3/32-12.22	0.01120	633.2	1.2	0.96	1.20
3.97	0.02820	1045.7	1.8	0.42	0.16
2.0	0.04740	1470.9	1.8	0.26	0.08
3.01	0.03546	1267.5	1.8	0.33	0.13
9.03	0.01522	1075.3	2.0	0.54	0.35

Table B-18. Side One: 1/8-15.2

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	608.1	0.1	0.18	0.08
1/10-19.35	0.00460	481.2	0.2	0.30	0.11
1/9-24.12	0.00397	503.3	0.2	0.37	0.18
3/8(b)-11.1	0.01012	463.6	0.6	0.49	0.24
3/4-11.1	0.01012	496.0	0.6	0.39	0.17
3/8-11.1	0.01012	461.3	0.6	0.50	0.25
3/16-11.1	0.01012	471.9	0.6	0.52	0.31
11.1	0.01012	579.7	0.6	0.26	0.09
1/2-11.1	0.01012	486.5	0.6	0.42	0.20
3/4(b)-11.1	0.01012	500.6	0.6	0.39	0.17
1/8-16.12T	0.00514	419.4	0.8	1.24	1.10
14.77	0.00848	527.9	0.8	0.45	0.22
30.33T	0.00401	370.0	0.8	1.21	0.63
1/6-12.18D	0.00885	438.2	0.8	0.74	0.39
6.2	0.01820	978.2	1.0	0.19	0.06
17.8-3/8W	0.00696	447.8	1.0	1.13	0.96
11.44-3/8W	0.01060	500.1	1.0	0.84	0.72
1/8-15.2	0.00868	489.2	1.0	1.00	1.00
15.08	0.00876	593.1	1.0	0.40	0.15
5.3	0.02016	763.2	1.1	0.28	0.07
11.11(a)	0.01153	505.4	1.2	0.57	0.19
3/32-12.22	0.01120	578.8	1.2	0.81	0.86
3.97	0.02820	1019.5	1.8	0.36	0.12
2.0	0.04740	1466.3	1.8	0.22	0.06
3.01	0.03546	1247.3	1.8	0.28	0.09
9.03	0.01522	1039.1	2.0	0.45	0.25

Table B-19. Side One: 15.08

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	1372.9	0.1	0.45	0.56
1/10-19.35	0.00460	1111.4	0.2	0.74	0.75
1/9-24.12	0.00397	1216.0	0.2	0.91	1.24
3/8(b)-11.1	0.01012	888.9	0.6	1.21	1.64
3/4-11.1	0.01012	892.5	0.6	0.96	1.15
3/8-11.1	0.01012	888.2	0.6	1.23	1.68
3/16-11.1	0.01012	922.7	0.6	1.29	2.10
11.1	0.01012	930.2	0.6	0.64	0.59
1/2-11.1	0.01012	895.9	0.6	1.05	1.34
3/4(b)-11.1	0.01012	897.7	0.6	0.95	1.15
1/8-16.12T	0.00514	965.6	0.8	3.07	7.48
14.77	0.00848	913.4	0.8	1.12	1.47
30.33T	0.00401	827.0	0.8	2.98	4.25
1/6-12.18D	0.00885	856.7	0.8	1.84	2.66
6.2	0.01820	1280.9	1.0	0.47	0.44
17.8-3/8W	0.00696	939.7	1.0	2.80	6.49
11.44-3/8W	0.01060	968.6	1.0	2.08	4.85
1/8-15.2	0.00868	992.4	1.0	2.47	6.77
15.08	0.00876	928.5	1.0	1.00	1.00
5.3	0.02016	1041.2	1.1	0.68	0.46
11.11(a)	0.01153	836.8	1.1	1.41	1.26
3/32-12.22	0.01120	1059.8	1.2	2.00	5.84
3.97	0.02820	1300.8	1.8	0.88	0.80
2.0	0.04740	1657.0	1.8	0.55	0.38
3.01	0.03546	1506.9	1.8	0.70	0.63
9.03	0.01522	1387.7	2.0	1.12	1.71

Table B-20. Side One: 5.3

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	2586.6	0.1	0.66	1.21
1/10-19.35	0.00460	2101.5	0.2	1.08	1.63
1/9-24.12	0.00397	2337.0	0.2	1.33	2.71
3/8(b)-11.1	0.01012	1518.4	0.5	1.77	3.58
3/4-11.1	0.01012	1479.5	0.5	1.41	2.50
3/8-11.1	0.01012	1520.1	0.5	1.80	3.66
3/16-11.1	0.01012	1590.0	0.5	1.90	4.58
11.1	0.01012	1452.7	0.5	0.94	1.28
1/2-11.1	0.01012	1502.0	0.5	1.53	2.92
3/4(b)-11.1	0.01012	1485.8	0.5	1.40	2.50
1/8-16.12T	0.00514	1767.3	0.7	4.50	16.30
14.77	0.00848	1473.8	0.7	1.64	3.21
30.33T	0.00401	1492.8	0.7	4.37	9.27
1/6-12.18D	0.00885	1462.4	0.8	2.69	5.79
6.2	0.01820	1742.0	0.9	0.70	0.96
17.8-3/8W	0.00696	1645.5	0.9	4.10	14.15
11.44-3/8W	0.01060	1638.8	0.9	3.05	10.57
1/8-15.2	0.00868	1713.3	0.9	3.62	14.76
15.08	0.00876	1411.4	0.9	1.47	2.18
5.3	0.02016	1455.3	1.0	1.00	1.00
11.11(a)	0.01153	1307.7	1.0	2.07	2.74
3/32-12.22	0.01120	1739.2	1.0	2.94	12.72
3.97	0.02820	1732.0	1.6	1.29	1.74
2.0	0.04740	2053.2	1.6	0.80	0.82
3.01	0.03546	1936.6	1.6	1.02	1.38
9.03	0.01522	1889.0	1.8	1.65	3.74

Table B-21. Side One: 11.11a

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	1269.9	0.1	0.32	0.44
1/10-19.35	0.00460	1017.5	0.2	0.52	0.60
1/9-24.12	0.00397	1103.8	0.2	0.64	0.99
3/8(b)-11.1	0.01012	820.0	0.5	0.85	1.31
3/4-11.1	0.01012	834.8	0.5	0.68	0.91
3/8-11.1	0.01012	818.6	0.5	0.87	1.34
3/16-11.1	0.01012	847.7	0.5	0.91	1.67
11.1	0.01012	893.3	0.5	0.46	0.47
1/2-11.1	0.01012	833.7	0.5	0.74	1.07
3/4(b)-11.1	0.01012	840.4	0.5	0.67	0.91
1/8-16.12T	0.00514	851.8	0.7	2.17	5.95
14.77	0.00848	853.8	0.7	0.79	1.17
30.33T	0.00401	731.3	0.7	2.11	3.39
1/6-12.18D	0.00885	777.8	0.7	1.30	2.12
6.2	0.01820	1270.8	0.8	0.34	0.35
17.8-3/8W	0.00696	836.1	0.9	1.98	5.17
11.44-3/8W	0.01060	876.3	0.9	1.47	3.86
1/8-15.2	0.00868	889.1	0.9	1.75	5.39
15.08	0.00876	880.5	0.9	0.71	0.80
5.3	0.02016	1014.8	1.0	0.48	0.37
11.11(a)	0.01153	779.0	1.0	1.00	1.00
3/32-12.22	0.01120	965.2	1.0	1.42	4.65
3.97	0.02820	1262.5	1.6	0.62	0.63
2.0	0.04740	1645.4	1.6	0.39	0.30
3.01	0.03546	1480.6	1.6	0.49	0.50
9.03	0.01522	1331.8	1.7	0.79	1.37

Table B-22. Side One: 3/32-12.22					
Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	941.1	0.1	0.23	0.10
1/10-19.35	0.00460	747.6	0.2	0.37	0.13
1/9-24.12	0.00397	798.0	0.2	0.45	0.21
3/8(b)-11.1	0.01012	643.5	0.5	0.60	0.28
3/4-11.1	0.01012	670.9	0.5	0.48	0.20
3/8-11.1	0.01012	641.3	0.5	0.61	0.29
3/16-11.1	0.01012	660.4	0.5	0.65	0.36
11.1	0.01012	749.8	0.5	0.32	0.10
1/2-11.1	0.01012	664.2	0.5	0.52	0.23
3/4(b)-11.1	0.01012	676.2	0.5	0.48	0.20
1/8-16.12T	0.00514	624.6	0.6	1.53	1.28
14.77	0.00848	695.8	0.7	0.56	0.25
30.33T	0.00401	541.9	0.7	1.49	0.73
1/6-12.18D	0.00885	605.4	0.7	0.92	0.46
6.2	0.01820	1153.0	0.8	0.24	0.08
17.8-3/8W	0.00696	633.7	0.9	1.40	1.11
11.44-3/8W	0.01060	684.1	0.9	1.04	0.83
1/8-15.2	0.00868	682.2	0.9	1.23	1.16
15.08	0.00876	745.2	0.9	0.50	0.17
5.3	0.02016	906.4	1.0	0.34	0.08
11.11(a)	0.01153	645.2	1.0	0.71	0.22
3/32-12.22	0.01120	769.1	1.0	1.00	1.00
3.97	0.02820	1158.7	1.5	0.44	0.14
2.0	0.04740	1591.8	1.5	0.27	0.06
3.01	0.03546	1389.7	1.5	0.35	0.11
9.03	0.01522	1198.5	1.7	0.56	0.29

Table B-23. Side One: 3.97

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	5022.5	0.1	0.52	0.70
1/10-19.35	0.00460	4028.6	0.1	0.84	0.94
1/9-24.12	0.00397	4503.6	0.1	1.03	1.56
3/8(b)-11.1	0.01012	2603.7	0.3	1.37	2.06
3/4-11.1	0.01012	2510.1	0.3	1.10	1.44
3/8-11.1	0.01012	2608.5	0.3	1.39	2.11
3/16-11.1	0.01012	2735.1	0.3	1.47	2.63
11.1	0.01012	2410.1	0.3	0.73	0.74
1/2-11.1	0.01012	2558.5	0.3	1.19	1.68
3/4(b)-11.1	0.01012	2519.3	0.3	1.08	1.44
1/8-16.12T	0.00514	3038.4	0.4	3.49	9.38
14.77	0.00848	2413.3	0.4	1.27	1.85
30.33T	0.00401	2531.4	0.5	3.39	5.33
1/6-12.18D	0.00885	2427.7	0.5	2.09	3.33
6.2	0.01820	2609.2	0.5	0.54	0.55
17.8-3/8W	0.00696	2711.5	0.6	3.18	8.14
11.44-3/8W	0.01060	2668.8	0.6	2.37	6.08
1/8-15.2	0.00868	2808.9	0.6	2.81	8.49
15.08	0.00876	2207.4	0.6	1.14	1.25
5.3	0.02016	2173.0	0.6	0.77	0.58
11.11(a)	0.01153	2037.7	0.6	1.61	1.58
3/32-12.22	0.01120	2756.7	0.6	2.28	7.32
3.97	0.02820	2414.3	1.0	1.00	1.00
2.0	0.04740	2771.0	1.0	0.62	0.47
3.01	0.03546	2657.0	1.0	0.79	0.79
9.03	0.01522	2633.0	1.1	1.28	2.15

Table B-24. Side One: 2.0

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	8701.8	0.1	0.83	1.48
1/10-19.35	0.00460	7014.0	0.1	1.35	1.99
1/9-24.12	0.00397	7911.8	0.1	1.66	3.30
3/8(b)-11.1	0.01012	4331.5	0.3	2.21	4.37
3/4-11.1	0.01012	4094.1	0.3	1.77	3.04
3/8-11.1	0.01012	4345.0	0.3	2.24	4.46
3/16-11.1	0.01012	4575.5	0.3	2.37	5.58
11.1	0.01012	3766.1	0.3	1.18	1.56
1/2-11.1	0.01012	4204.7	0.3	1.92	3.56
3/4(b)-11.1	0.01012	4104.7	0.3	1.75	3.05
1/8-16.12T	0.00514	5288.6	0.4	5.62	19.86
14.77	0.00848	3884.9	0.4	2.05	3.92
30.33T	0.00401	4378.6	0.5	5.46	11.29
1/6-12.18D	0.00885	4062.4	0.5	3.36	7.06
6.2	0.01820	3662.5	0.5	0.87	1.17
17.8-3/8W	0.00696	4622.4	0.6	5.12	17.24
11.44-3/8W	0.01060	4454.3	0.6	3.82	12.88
1/8-15.2	0.00868	4747.5	0.6	4.53	17.98
15.08	0.00876	3418.3	0.6	1.83	2.66
5.3	0.02016	3146.4	0.6	1.25	1.22
11.11(a)	0.01153	3232.4	0.6	2.59	3.34
3/32-12.22	0.01120	4524.2	0.6	3.67	15.50
3.97	0.02820	3388.2	1.0	1.61	2.12
2.0	0.04740	3617.3	1.0	1.00	1.00
3.01	0.03546	3598.9	1.0	1.27	1.68
9.03	0.01522	3778.6	1.1	2.06	4.55

Table B-25. Side One: 3.01					
Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	6561.5	0.1	0.65	0.88
1/10-19.35	0.00460	5277.0	0.1	1.06	1.18
1/9-24.12	0.00397	5928.0	0.1	1.30	1.96
3/8(b)-11.1	0.01012	3328.2	0.3	1.73	2.60
3/4-11.1	0.01012	3175.1	0.3	1.39	1.81
3/8-11.1	0.01012	3336.6	0.3	1.76	2.65
3/16-11.1	0.01012	3506.6	0.3	1.86	3.32
11.1	0.01012	2981.0	0.3	0.93	0.93
1/2-11.1	0.01012	3249.3	0.3	1.50	2.12
3/4(b)-11.1	0.01012	3185.0	0.3	1.37	1.81
1/8-16.12T	0.00514	3979.4	0.4	4.41	11.82
14.77	0.00848	3031.6	0.4	1.60	2.33
30.33T	0.00401	3304.2	0.5	4.28	6.72
1/6-12.18D	0.00885	3112.9	0.5	2.64	4.20
6.2	0.01820	3055.6	0.5	0.68	0.70
17.8-3/8W	0.00696	3511.6	0.6	4.02	10.26
11.44-3/8W	0.01060	3417.4	0.6	2.99	7.67
1/8-15.2	0.00868	3621.0	0.6	3.55	10.70
15.08	0.00876	2717.5	0.6	1.44	1.58
5.3	0.02016	2584.8	0.6	0.98	0.73
11.11(a)	0.01153	2540.2	0.6	2.03	1.99
3/32-12.22	0.01120	3498.5	0.6	2.88	9.23
3.97	0.02820	2827.1	1.0	1.27	1.26
2.0	0.04740	3131.5	1.0	0.78	0.60
3.01	0.03546	3057.2	1.0	1.00	1.00
9.03	0.01522	3117.9	1.1	1.61	2.71

Table B-26. Side One: 9.03

Surface Designation	$4r_h$ (ft)	Volume (ft^3)	b_2/b_1	K_{i2}/K_{i1}	K_{f2}/K_{f1}
1/10-19.74	0.00400	4637.8	0.1	0.40	0.33
1/10-19.35	0.00460	3703.7	0.1	0.66	0.44
1/9-24.12	0.00397	4125.3	0.1	0.81	0.72
3/8(b)-11.1	0.01012	2402.2	0.3	1.07	0.96
3/4-11.1	0.01012	2333.2	0.3	0.86	0.67
3/8-11.1	0.01012	2405.5	0.3	1.09	0.98
3/16-11.1	0.01012	2518.0	0.3	1.15	1.22
11.1	0.01012	2275.8	0.3	0.57	0.34
1/2-11.1	0.01012	2371.5	0.3	0.93	0.78
3/4(b)-11.1	0.01012	2342.8	0.3	0.85	0.67
1/8-16.12T	0.00514	2742.6	0.4	2.73	4.36
14.77	0.00848	2242.8	0.4	0.99	0.86
30.33T	0.00401	2286.5	0.4	2.66	2.48
1/6-12.18D	0.00885	2220.5	0.4	1.63	1.55
6.2	0.01820	2531.7	0.5	0.42	0.26
17.8-3/8W	0.00696	2454.2	0.5	2.49	3.79
11.44-3/8W	0.01060	2435.5	0.5	1.86	2.83
1/8-15.2	0.00868	2550.7	0.5	2.20	3.95
15.08	0.00876	2070.6	0.5	0.89	0.58
5.3	0.02016	2080.7	0.6	0.61	0.27
11.11(a)	0.01153	1889.4	0.6	1.26	0.73
3/32-12.22	0.01120	2523.2	0.6	1.78	3.40
3.97	0.02820	2311.2	0.9	0.78	0.47
2.0	0.04740	2713.9	0.9	0.49	0.22
3.01	0.03546	2572.4	0.9	0.62	0.37
9.03	0.01522	2496.7	1.0	1.00	1.00

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